Chapter 1

Future Sustainability of the Sugar and Sugar−Ethanol Industries

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Like many other food and chemical industries, the sugar and sugar−ethanol industries are facing important sustainability issues. The relatively low and fluctuating profit for sugar, the world-wide impetus to produce alternatives to petroleum-based fuels and reduce green house gases, and water- and energy-intensive factories and refineries are putting pressure on the industries to diversify for sustainability. In sugar manufacture, there is a world-wide trend to produce very high purity (VHP) and very low color (VLC) raw sugars for vertical integration from the field to white sugar. All biomass from the sugarcane and sugar beet plants including tops and leaves, are being intensely investigated for utilization, including cogeneration of both heat and bioelectricity in some countries. Sugar, in a few years, is expected to be the "new oil" as sugar is a superior feedstock for the production of platform chemicals for the manufacture of a range of end-products, e.g., bioplastics, industrial solvents, and chemicals. Sugarcane, sugar beet, and sweet sorghum fit well into the concept of a renewable carbohydrate feedstock for fuel ethanol production because of their availability, and they are amongst the plants giving the highest yields of carbohydrates per hectare. Green sustainability criteria are now in place in the European Union for the EU biofuels sector that have to be met to count against national biofuel targets. Processes to convert high-fiber, energy sugarcanes and sugar beets as well as traditional cellulosic

by-products into fuel ethanol have been developed but are not yet commercialized.

Introduction

Sucrose (α-D-glucopyranosyl-(1→2)-β-D-fructofuranose) is ubiquitously known as common table sugar, and crystalline sucrose is primarily produced industrially from sugarcane (*Saccharum officinarum*) and sugar beet (*Beta vulgaris*) (Figure 1).

Like many other food and chemical industries, the sugar industry and sugar−ethanol industries are currently facing tough sustainability issues. Sustainability in this chapter is defined as the balancing of the three, interdependent pillars of the environment (ecology), society, and the economy (Figure 2). For some industries the core principles for sustainable manufacture are renew, reuse, and and recycle, which are applied to every production step and business practice (*1*).

Figure 1. Sugarcane harvested into billets (top) and sugar beets being delivered for processing (bottom).

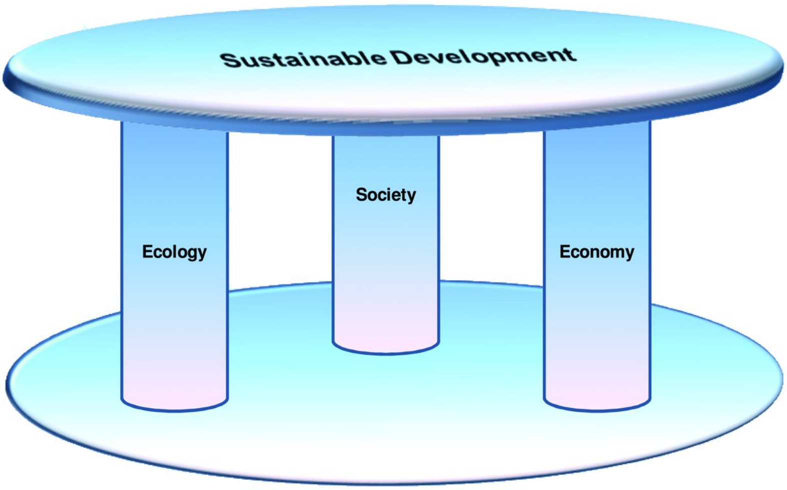

Figure 2. Sustainability focuses on the triple bottom line: the integration of (i) ecological integrity, (ii) social responsibility and (iii) economic viability.

Table I. Unsustainable Versus Sustainable Mindsets and Practices in the Current Sugar Industry. (Adapted from (*3*))

Key dimension	*Unsustainable*	*Sustainable*
Society/Policy Goals	Economic growth	Growth in well-being
Approach to Nature	Control over nature	Work with nature
Predominant Work Mode	"Big is Better"	"Smart is Better"
Focus on Business Activities	Goods	Services, needs
Energy Sources	Fossil fuels	Renewable energy (including biofuels)
Predominant Chemistry	Energy intensive	Low energy
Waste Production	High waste	No waste
Typical Materials	Iron, steel and cement	Bio-based materials

The twentieth century saw enormous growth in chemicals manufacturing which fed the parallel growth in the developed world. However, the growth came at a cost. Inefficient processes leading to unacceptable levels of pollution, hazardous operations resulting in a number of well-publicized disasters, inadequate product testing causing often irrational public concerns over product safety, have all led to an exponential growth in chemicals legislation (*2*). Chemical industries, including the sugar and emerging sugar–ethanol industries, now need to achieve environmentally acceptable and economically viable manufacturing in a tough legislative framework while meeting the high demand of a growing

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population. Sustainable production of sugar, ethanol and other bioproducts from sugar crops, will only be realized through a reassessment of the entire chemical product life-cycle from resources, to manufacturing and production, through to product use and ultimate fate (*2*).

To achieve sustainable sugar and sugar−ethanol industries several critical changes are required both in mindset and practice that are listed in Table I.

This chapter describes current trends and needs in the sugar and sugar−ethanol industries that are expected to strongly contribute to their sustainability.

Industrial Sugar Production: Background

Commercially available sucrose has very high purity (>99.9%) making it one of the purest organic substances produced on an industrial scale. To obtain such a pure product from both sugarcane and sugar beet, rather complex isolation and purification process units are followed. Industrial sucrose production is essentially a series of separations of non-sucrose compounds (usually termed non-sugars or impurities) from sucrose, and the chemistry of the sequential process units is designed for maximum removal of non-sugars with minimum destruction of sucrose (Figure 3). Sugarcane is grown in tropical and sub-tropical areas of the world and processing often occurs in two stages. Firstly, the juice is extracted from sugarcane (sucrose yields range between 10-15% weight of sugarcane) and converted to raw sugar (~97-99% pure sucrose; golden yellow/brown crystals) at factories. Secondly, after raw sugar has been transported to a refinery, it is refined using very similar unit processes used in raw sugar manufacture, to the familiar white, refined sugar (>99.9% sucrose). In some tropical areas of the world, particularly Asia, plantation white, mill white, or direct white sugar (>99% sucrose with a higher color than white, refined sugar) is produced directly from sugarcane (*4*).

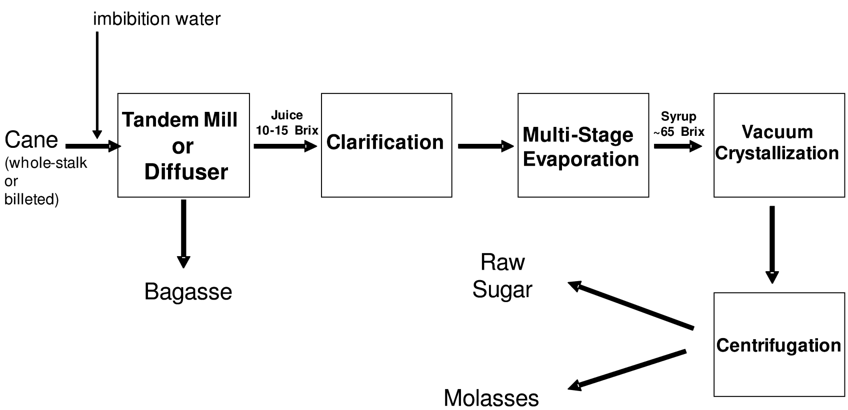

Figure 3. Basic scheme of the raw sugar manufacturing process in a sugarcane factory (4). Brix is % dissolved solids.

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In comparison to sugarcane, sugar beets are grown in more temperate areas and are processed directly into white sugar (>99.9% sucrose) at nearby factories. Production of refined sugar from sugar beets has some similarities to refined cane sugar production. However, disimilarites exist as sugar beet is a tuberous root and sugarcane a grass. Sugar beets are harvested defoliated and delivered to the factory, with excess sugar beets stored in long-term storage piles on factory or remote grounds. Sugar beets are introduced to the factory, washed, and sliced into "V" shaped cossettes. Cossettes are added to a diffuser and sucrose (~98%) and impurities are extracted with hot water. Diffusion juice contains ~12% sucrose and 2% soluble impurities on sugar beet weight, and is heated to ~85 °C before it is purified with a double-carbonatation clarification process. The resulting clarified "thin" juice is then concentrated from ~14 to ~60-65 Brix ("thick" juice) across multiple-effect evaporators, then triple-crystallized and centrifuged to produce white, refined sugar (>99.7% purity). In some sugar beet factories additional purification steps are employed, such as color removal with ion-exchange resins or carbon adsorbants. Additionally, sucrose is also recovered from beet molasses with chromatography, a process that is much easier in sugar beet than sugarcane processing. For more detailed information on the industrial production of sucrose from sugarcane and sugar beet, the reader is referred to other comprehensive texts (*4–8*).

The major by-products of industrial sucrose production are cane bagasse, beet pulp, and molasses. Minor by-products include fly ash, filter cake, lime and calcium carbonate residues. By volume, bagasse is the most important by-product and is the primary source of fuel for the generation of steam and bioelectricity to run sugarcane factories. Beet pulp is a source of animal feed as wet pulp, pressed pulp silage, and dried pulp, with or without added molasses. Molasses is presently the most valuable by-product of sugar manufacture and exists in a range of grades: edible molasses, cane and beet molasses, and refinery molasses. It is used as an animal feed additive, in the industrial production of rum and other beverage alcohols, bakers' yeast, citric acid, and other fermentation processes.

VHP (Very High Pol) and VLC (Very Low Color) Sugar Production–A Sustainable Trend

There is presently a trend in the U.S. and worldwide to manufacture VHP and VLC raw sugars for supply to refineries, i.e., a trend of vertical integration from the field to the white sugar output. Furthermore, a concomitant trend exists to build refineries of the VHP/VLC cane raw sugar close to the consumption areas to satisfy the needs of the food industry. This trend to integrate factory and refinery operations began in Australia in the mid 1990's (*9*) to reduce the overall cost structure and enhance product quality. There is also a growing demand for exports of VHP and VVHP (very, very high pol) raw sugars, particularly from Brazil, mainly for overseas markets. In the U.S., many factories have combined into the Louisiana Sugar Cane Products, Inc. (LSCPI) and are investing, with Imperial Sugar and Cargill companies, in a new sugar refinery in Gramercy, LA, which is expected to be operational in mid-to-late 2011 (*10*). Some refineries also want lower ash concentrations in the VHP/VLC sugar because (a) some of the refined sugar will be manufactured into liquid sugar, which requires low ash, and (b) lower ash is needed for short, medium, and long term refinery strategies (Chapman, LSCPI, personal communication). The request for the supply of such higher quality raw sugars is expected to create additional efficiencies at the new refineries, particularly at the early, energy-intensive affination stage. The higher quality raw sugars will also allow factory processors to gain premiums from the new refineries. Furthermore, manufacture of higher quality raw sugars at the factory where the energy source is the sustainaible, renewable by-product bagasse (Figure 3), will save fossil energy utilization by the refiners.

One of the main keys to manufacturing VHP/VLC sugar is the removal of color. While color removal at the refinery is mostly perfected (*11*), the processes are capital- and equipment-intensive, which further justifies the refiners request that more of the color removal work be undertaken at the factory. Current color removing strategies at the factory can be separated into three categories: (i) improved unit process operations and designs, (ii) chemical processes, and (iii) physical processes (*11*, *12*). However, all three categories are typically expensive. Moreover, great variations in the color of the raw sugars produced still exist because of the large variations in the quality of the cane supply (*12*, *13*). Muir and Eggleston (*12*) recently suggested that even a small reduction, e.g., <10% in total trash levels processed at the factory, could be more efficient and cost-effective than other factory color removal processes and have the additional advantages of improving sugar yields and ash contents.

Large-Scale Cogeneration of Bioelectricity from Sugarcane Bagasse

Most sugarcane factories cogenerate steam and bioelectricity from bagasse to run the factory and, in the early years of the sugar industry they were viewed as the original cogenerators of the world (*14*). Nowadays, some countries' sugar industries, e.g., Mauritius, Brazil, India, and the Philippines, also operate large-scale cogeneration and sell the surplus electricity to the local or national grid, and there is great potential for many other countries to follow. Furthermore, cogeneration contributes to sustainability as the negative environmental impact of Green House Gases (GHGs) from traditional thermal power stations are reduced (*15*). A case example is the Mauritius sugar industry. In a typical year, 19-21% of the electricity in Mauritius is generated from bagasse. Because of the seasonal character of sugarcane, the contribution of bagasse to the Mauritian grid fluctuates seasonally. Thus, to ensure year-round supply of electricity, the plants co-fire with coal (*16*).

One of the main technological improvements leading to higher efficiency cogeneration of bioelectricity from bagasse has been the use of new high-pressure boilers, i.e., up to 82-92 bars (producing superheated steam at 525 °C). Efficiency gains leading to a surplus of electricity generation for export to the grid have also been accomplished through the retro-fitting of turbo-alternators with high steam pressure/temperature (*14*), the optimization of other process parameters, including steam consumption, increasing fiber content of cane through genetic manipulation, lower moisture content of bagasse, and reducing the consumption of electricity in the factory tandem mill and power plant (*15*). The development of year-round bagasse cogeneration in Mauritius was promoted by providing incentives for the cogenerator and a number of policies and policy instruments drivers: (i) reform of the Mauritian sugar industry, (ii) planning and regulatory paths, (iii) financial and tax incentives, (iv) power purchase agreements including the pricing of electricity, (v) research and development, (vi) equity participation to broaden ownership of the industry, and (vii) carbon dioxide emission reductions (*16*). This will be discussed in much further detail in Chapter 4 of this book (*17*).

Sugarcane trash biomass, e.g., leaves and tops, from the fields allows even more scope for cogeneration (*14*); a 2007 study in Brazil (*18*) showed utilization of trash with bagasse doubled the MWh production of energy compared to when just bagasse alone was utilized. However, the sugar industry's world-first attempt in Australia to send the entire green cane crop, i.e., with all the trash, to the factory to fuel its electricity cogeneration plants, was halted in November 2009 (*19*) because less than acceptable sugar recoveries occurred in factories. This was "extremely disappointing" to growers who had spent millions of dollars modifying equipment to no gain and now have debts (*19*). A cleaning plant may be necessary to remove the trash at the factory so it is not processed (*19*). This is discussed more fully in the next section.

A New Reverence for Sugarcane Trash (Leaves and Tops)

Although sugarcane trash continues to be under-utilized in numerous countries there is a growing reality that it represents a rich source of biomass for production of a multitude of biomaterials, including bioelectricity as described in the above section, cellulosic ethanol, and biochar. Moreover, separation of trash from stalks before processing would dramatically improve the efficiency of processing and the quantity and quality of raw and VHP sugar produced (*12*). Sugarcane trash includes green and brown dried leaves plus growing point region [apical internodes] or top. Compared to bagasse, sugarcane trash contains approximately the same or slightly less lignin and is, therefore, as easily degraded. Singh *et al.* (*20*) recently reported the effect of biological treatments on sugarcane trash for its conversion to fermentable sugars.

The use of sugarcane trash as a biomass source for bioelectricity, cellulosic ethanol, and biochar production is dependent on the amount of dry mass available. Typical percent tissue weights on a dry mass basis for U.S. and South African commercial sugarcane varieties grown mid-season are listed in Table II. It can be seen (Table II) that varietal variation occurs, and U.S. sugarcane had ~34% total trash compared to 41% for the South African variety (Table II). Thus, over one third of the total dry mass from sugarcane is from trash. In the case of the U.S. varieties the green leaves deliver the most dry mass of all the trash tissues (*21*), whereas for the South African variety that was ~23 months age compared to 12 months age for U.S. cane varieties (Table II) the growing point region delivered

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the most dry mass. The amount of available dry mass from trash will also fluctuate across the season.

Often sugarcane trash is burned in the field or left as a cover in the field after harvesting to contribute as an organic soil fertilizer or delivered to the factory where it detrimentally affects upstream and downstream processing (*21*). Leaving excess trash on the field can reduce subsequent ratoon (new crop) yields (*22*). Although some trash should be utilized as a soil fertilizer there is still plenty available for use as biomass. Furthermore, the world-wide shift away from the harvesting of burnt to unburnt (green) sugarcane for environmental reasons means even more trash is becoming available to collect in the field or at the factory.

For trash to work as a biomass source, research into economical ways to collect and transport excess trash in the field is needed, preferably after solar drying in the field to create greater dry mass (*24*). Trash that is harvested and delivered with the stalks at the factory could also be separated there; trash separation technologies at the factory are available (*25*), including dry cleaning before the sugarcane is shredded. However, questions still remain on how efficiently trash separation technologies perform while *not* removing valuable sucrose from the stalks (*22*, *26*). Furthermore, the excessively large piles of trash that could be created at the factory will have to be utilized quickly (*22*). Trash shredders can reduce trash to bagasse-like consistency (*25*).

Table II. Average % Tissue Weights on a Dry Weight Basis (Potential Biomass) of Field Sugarcane Varieties in the U.S. and South Africa (Mid-season). (From Eggleston *et al.* (*22*) and Muir *et al.* (*23*))

Tissue	*% Tissue on a Dry Weight Basis*[ab]			
	U.S. (Louisiana)			***South Africa (Midlands)***
	HoCP 96-540[c]	*L 99-226*[c]	*L 99-233*[c]	*N12*[c]
Stalk	63.7	64.0	71.0	58.9
Growing Point Region	4.8	4.5	4.8	22.4
Green Leaves	17.2	20.7	16.2	13.6
Brown Leaves	14.3	10.7	8.1	5.2
Total Trash: GPR + GL + BL	35.3	35.9	29.1	41.1

[a] N=4 [b] % tissue on a dry weight basis was calculated as wet weight x (100-% moisture content)/Total plant dry weight x 100 [c] The Louisiana season is 3-months from Oct to Dec (winter). The South Africa season is 8-months from April to Dec; sampling occurred in June (winter). U.S. sugarcane was ~12 months age whereas N12 was ~23 months.

Value Added Products from Sucrose

Value-added products from sucrose that meet existing needs can increase the demand, value, and consumption of sucrose, and improve the competitiveness of the sugar industry in a world increasingly turning to agriculturally-derived chemicals from renewable feedstocks because of the surging costs and detrimental climate impacts of petroleum and gas feedstocks. However, only a small percentage of the sugar produced in the world is used in non-food applications, with ~1.7% at present in the U.S. (*27*). This is unfortunate as much research effort and funds have been expanded on the identification and development of value-added products from sucrose. Part of the reason for such little impact of this research is that the scientists inventing the products have not fully considered the market, and do not have the business acumen to sell such products to industry (*4*). More involvement by industry, particularly at the conception phase, would help to gain more impact (*4*).

Sucrose is a likely source for many value-added products because of its chemical and enzymatic reactivity. The basis for the reactivity of sucrose is the eight hydroxyl groups present on the molecule. Generally, the three primary hydroxyls have greater reactivity but they often prove a hindrance as they are difficult to react exclusively (*28*). The synthesis of an enormous number of sucrose derivatives is possible; substitution with just one group type could theoretically give two hundred and fifty five different compounds! Moreover, the alcohol group can be derivatized to form esters, ethers, and substitution derivatives (*28*). Sucrose can be readily degraded by acids, oxidizing agents, alkalis, and catalytic hydrogen to compounds of lower molecular weight. Sucrose is also an exceptional molecule for enzymatic synthesis reactions (*27*, *29*). Sucrose can act as a donor molecule for enzymatic transfer reactions to form oligosaccharides and polysaccharides. Products formed from chemical and enzymatic reactions will be discussed in chapter 15 of this book including the manufacture of bioplastics and biofibers (*30*).

Further Optimization of Sugar Processing

Like for other chemical industries, there is always room for improvement in sugar processing. The large topic is beyond the scope of this chapter but two critical areas needing improvement – (a) measurement of deterioration at the factory and (b) optimized application of enzymes - are briefly described in the next two sub-sections.

Improved Control of Sugarcane and Sugar Beet Deterioration

Better control and processing of sugarcane and sugar beet deterioration will contribute to the sustainability of the sugar industry. The delivery of consignments of deteriorated sugarcane or sugar beet to factories in many countries still often detrimentally affect multiple process units, reduce valuable sucrose and ethanol yields, and even lead to a factory shut-down. Until the last few years, there was no validated, reliable, rapid, easy, and inexpensive method to measure deterioration

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at the factory. This has meant that factory personnel have not been able to screen individual consignments of sugarcane or sugar beet and, thus, they do not know which consignments will detrimentally affect processing and are unable to reject unsuitable consignments. Furthermore, grower payment formulas incorporating a deterioration quality parameter may serve as a deterrent against the delivery of overly deteriorated sugarcane, improve processing, and encourage better sugarcane management as prevention is always better than the cure.

The major (but not sole) contributor to sugarcane and sugar beet deterioration in the U.S. and many other countries, particularly where warm and humid conditions prevail, is infection by hetero-fermentative *Leuconostoc mesenteroides* lactic acid bacteria (*31–33*). Previously, the sugar industry has considered dextran, a viscous glucopolysaccharide, as the major deterioration product of a *L. mesenteroides* infection. Current methods to determine dextran, however, are either too time consuming and complicated, not specific enough, too expensive, too imprecise, or too difficult in the interpretation of results (*33*). Moreover, none of these dextran methods can be used in a payment system for growers. In recent years it has emerged that mannitol, a sugar alcohol, is also a major degradation product of *L. mesenteroides* sugarcane deterioration, sugar beet deterioration, and even some bacterial contamination of fuel ethanol produced from sugarcane (*33*). Mannitol is also produced by other hetero-fermentative *Lactobacillus* bacteria, although *L. mesenteroides* is the greatest producer (*34*). An enzymatic factory method that is rapid, simple, accurate, and inexpensive is now available to measure mannitol in juices (*33*). Greater than ~500 ppm/Brix of mannitol in sugarcane juice predicts downstream processing problems, but this threshold value may vary from region to region (*33*). The increasing awareness of how mannitol detrimentally effects processing is fully discussed in Chapter 13 of this book (*35*).

Optimized Industrial Enzyme Applications

In the sugar industry, α-amylase is frequently used to hydrolyze starch into lower MW (molecular weight) dextrins and maltooligosaccharides in sugarcane factories, and dextranase is used to hydrolyze dextran into lower MW dextrans and isomaltooligosaccharides when sugarcane or sugar beet deterioration has occurred. Unfortunately, large enzyme manufacturing companies only regard the sugar industry as a small enzyme market. As a consequence, there has been limited or no research and development by such companies to tailor the properties of commercial α-amylases and dextranases to the harsh sugar processing conditions, and none is expected in the near future. Thus, both α-amylases and dextranases used in the sugar industry were developed for larger markets, e.g., α-amylases for the detergent industry, which has caused their sub-optimum and mis-applications in sugar factories (*36*, *37*). For this reason, since 2005 factory optimization studies for both α-amylase and dextranase in sugar processing were conducted (*38–40*). These have included providing methods to measure the activities of these commercial enzymes at the factory. Results from these studies have already positively impacted the industry, and further optimization may be achieved by installing serpentine pipes to increase mixing of the enzyme

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and substrate and reduce the need for more retention time in the factory, as well as applying promising low level, uniform ultrasound technology (*41*). More long-term solutions to overcome the non-tailored processing properties of α-amylases and dextranases in the sugar industry could be protein engineering of the enzymes. Protein engineering techniques include site-directed mutagenesis and random mutagenesis (directed evolution) (*36*).

Sugar−Ethanol Industries

Continued reliance on fossil fuel energy resources is unsustainable, owing to both depleting world reserves and the GHG emissions associated with their use, as well as national security. Consequently, there are currently vigorous research initiatives aimed at developing renewable and potentially carbon neutral, solid, liquid and gaseous biofuels as alternative energy resources. Sugar crops, mainly sugarcane, sugar beet, and sweet sorghum (*Sorghum bicolor*), fit well into the emerging concept of renewable carbohydrate feedstocks for alternative fuels because of their availability, that they are amongst the plants giving the highest yields of carbohydrates per hectare, have high sugar content and are remunerative for growers.

First Generation Biothanol from Sugar Crops

As of January 2010, approximately 50% of the world's fuel ethanol production (mostly first generation) was from sugar crops utilizing conventional fermentation, with the remaining 50% from starchy grain crops (Table III). Sugar crops have the advantage over grain crops because they can be grown in a much larger area of the world (*42*) and are directly fermentable. Although in the U.S., the dominant feedstock for ethanol production is corn (*Zea mays*) grain, most other ethanol producing countries use sugarcane and sugar beet as their primary feedstocks (Table III). Both Brazil and India have large-scale sugarcane based fuel ethanol production (Table III). European fuel ethanol production has continued to increase strongly in the last three years because the new EU Sugar Regime has driven major restructuring of the European sugar industry (*43*). The new EU Regime rules allow non-sugar quota beet to be produced for industrial use - mostly ethanol production. Developments are also taking place at European sugar−ethanol plants to recover carbon dioxide produced by the plant to produce a liquified CO_2 value-added product, as well as make use of *all* the materials delivered to and generated at the plant (*43*).

Since 2006 there has been a near doubling of European Union (EU) production (*44*, *45*), mostly because of robust growth in France and Germany, and more than twenty sugar beet ethanol plants now exist in Europe. The EU Renewable Energy Directive (RED) has recently put forth sustainability criteria for the EU biofuels sector that have to be met to count against national biofuel targets (*46*). The sustainability criteria have three elements (*46*):

- Obigatory minimum Green House Gas (GHG) savings

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- Restrictions on land use for growing biofuel crops
- Social standards which have to be met

The most tangible criteria is the GHG saving of at least 35% which a given biofuel has to achieve to comply with the RED, which will rise to 50% in 2017 for existing plants. Ethanol from sugar beet and even more so from sugarcane exceed this 35% threshold by a large margin (*46*).

Currently, the U.S.A. is a net importer of energy and there is a goal to be completely independent and sustainable in energy production.

In recent years, there has been a dramatic increase in interest of sweet sorghum for large-scale conventional bioethanol manufacture (*47*, *48*) especially when integrated with sugarcane (*49*). One sugarcane-sweet sorghum industrial plant is currently under construction Florida. Highlands Envirofuels company is constructing a plant (20 million gal) northwest of Lake Okeechobee, Florida, after receiving a U.S. $7 million Florida State grant in 2008 (*50*). As sugarcane factories sit idle for many months of the year, processing of sweet sorghum to syrup in sugarcane factories before or after the harvest would allow for the greater use of capital equipment. Converting sugarcane and sweet sorghum juice to syrup that can be stored is one way of making the feedstock available year-round.

The use of first generation bioethanol in the transport sector has shown rapid global growth in recent years. It is projected that the growth in its production and consumption will continue (*51*) but its contribution toward meeting the overall energy demands in the transport sector will remain limited because of (i) competition with food and fiber production for the use of arable land, particularly in vulnerable regions of the world, (ii) regionally constrained market structures, (iii) lack of well managed agricultural practices in emerging economies, (iv) high water and fertilizer requirements, and (v) a need for conservation of biodiversity. However, some countries have the natural resources to grow large amounts of first generation biofuel crops without jeopardizing food production (*52*). For example, less than 7% of current Brazilian agricultural land is needed to expand sugarcane derived ethanol for the displacement of a further 5% of projected gasoline use by 2025 (*52*).

Second Generation Bioethanol from Sugar Biomass Crops

Second generation, advanced biofuels including bioethanol and biobutanol, derived from wastes, residues, and non-food cellulosic and lignocellulosic feedstocks address some of the problems associated with first generation biofuels, e.g., the strain on world food markets, contribution to water shortages and destruction of the world's forests (*52*). Second generation ethanol production from sugar biomass crops offers advantages over first generation ethanol because (i) lignocellulosics and cellulosics are abundant and less expensive than agricultural food feedstocks, (ii) they have a lot of potential growth, and (iii) can be grown in marginal lands that often require less fertilizer and water inputs (*42*).

The different technological steps required for the sustainable production of second generation bioethanol from sugar biomass crops are illustrated in Figure 4 as well as the need for an integrated research approach. However, the processing technology for conversion in the most part has not reached commercial scales. Currently, the production of second generation biofuels are still in the research and development or demonstration phases (*42*). Furthermore, commercialization of second generation bioethanol will depend mostly on economic factors such as values for agricultural feedstocks that have been estimated to range between 50-80% of the total ethanol's cost (*53*), government tax incentives for ethanol production, and mandatory ethanol/gas blends (*54*).

Table III. World fuel ethanol production by country in 2009. (From: F. O. Lichts World Sugar Statistics (*45*))

Country	*Million cubic meters per year*	*Percent of world production*
United States (*corn*)	**41,072**	**46.8**
Brazil (*sugarcane juice and molasses*)	**27,165**	**31.0**
China (*corn and wheat*)	**4,450**	**5.1**
India (*sugarcane molasses*)	**1,725**	**2.0**
France (*sugar beets*)	**1,850**	**2.1**
Germany (*sugar beets*)	**1,040**	**1.2**
World Total:	**87,703**	**100.0**

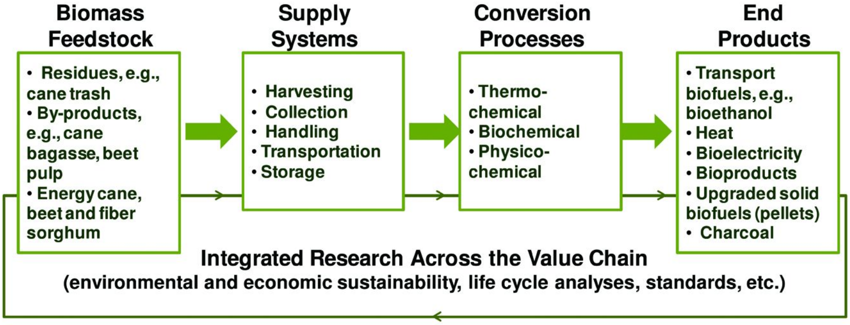

Figure 4. Sustainable biomass-based technologies for the second generation, sugar−ethanol and related industries. To achieve success, different fields of research must be integrated. Adapted from EUBIA (55).

Energy Sugar Crops for Emerging Second Generation, Cellulosic-Ethanol Industries

For truly sustainable sugar and sugar‒ethanol industries, research is needed to find the most profitable, productive and responsible ways to manage the natural-resource base so that production of sugar crops can be more sustainable. New genetic lines of crops are being developed that yield well under various stress conditions and have advantageous processing characteristics (*56*). Other improved agricultural practices can also reduce dependence on pretroleum-based agricultural chemicals. Moreover, it is the close relationship among the available amount of light, water, and nitrogen inputs and the amount of plant mass that they can produce – not human demand – that will determine how much biofuel the world can produce (*57*). Conversely, as crop residues of sugarcane and sugar beet are being proposed for ethanol production and other biofuels, a delicate balance has to be struck between how much is removed for energy and how much is left on the ground to protect soil from erosion, maintain soil organisms, and store carbon in the soil.

High-fiber "energy" or "biomass" crops, sugarcane, sugar beet and fiber sorghum can be converted to second generation cellulosic fuel ethanol as well as energy and bioelectricity. Companies and government agencies in several countries are currently sponsoring research into the development of energy canes and sugar beets. Processes to convert energy canes and beets into fuel ethanol are under intense investigation (*29*, *58*). The challenge is to develop energy crops with a suite of desirable physical and chemical traits while increasing biomass yields by a factor of two or more (*59*). Only little work has been accomplished on the breeding and cultivation of sugarcane and sugar beet for increased biomass yields. Thus, the time is ripe for intensive breeding of energy cane and beet varieties.

Energy Canes

In sugarcane, more rapid genetic gain can occur for total biomass yield than for sugar yield because growth does not have to be intentionally restricted during the life cycle of the crop and a wider array of germplasm of potential value is available to the breeder once stringent standards for sucrose and fiber levels are relaxed. A few energy cane varieties have already been developed and released (*60*) for the Louisiana, U.S., sugar industry in a cooperative effort between the USDA's Agricultural Research Service's (ARS) Sugarcane Research Unit, the Louisiana State University's (LSU) Agricultural Center, and the American Sugar Cane League of the U.S.A. Inc. During the 13-year selection process for varietal development, the sugar yield potentials of candidate varieties are compared to commercial standards. Often varieties are discarded because their fiber levels exceed 16%, a level which raw sugar manufacturers consider unacceptable for processing (*48*). Some of these discarded varieties continue to be used as parents in the breeding programs conducted by ARS and LSU because of their positive attributes. Three of the high fiber sugarcane varieties (L 79-1002, HoCP 91-552, and Ho 00-961) were released for commercial planting in 2007 (*60*) produce dry biomass yields in excess of 25 tonnes/ha. As marginal land to grow energy canes in Louisiana are mostly north and, therefore, colder during the winter, a major emphasis of the breeding program is to breed for cold tolerance.

Energy Beets

Higher biomass yields for energy beets are also possible using fodder beet germplasm as a parent in hybrids with sugar beet (*61*, *62*). Biomass yield potential is dependent upon interception of solar radiation which gives beets grown in areas with long growing seasons a decided advantage. Winter beets in the U.S. have a longer growing season and, therefore, a much higher yield potential (*42*).

In the current economic situation, most U.S. growers want beets that can be grown for either sucrose or ethanol, ensuring flexibility. Sugar beet pulp and molasses are also potentially excellent feedstocks for ethanol (*42*). It makes economic sense to co-locate ethanol plants or at least enzymatic digestion facilities next to sugar beet factories where the pulp is produced. As with all potential feedstocks, economics will determine the feasibility of developing the sugar beet crop as an ethanol feedstock (*63*).

Future Platform Chemicals from Sugar Industry Biomass

Novozymes CEO Steen Riisgaard recently said "in a few years sugar [crops] will be the new oil" as sugar is a superb feedstock for the production of platform chemicals for the manufacture of a range of end-products, e.g., bioplastics, industrial solvents, and chemicals (*3*). Efforts in "green chemistry" have been ramped up to transform crop biomass, e.g., from sugar crops, into the basic chemical ingredients that go into many everyday products (*64*). One of the major bottlenecks to using cellulosic biomass has been the depolymerization step. Low, moderate (~500 °C) and high temperatures (gasification temperatures) are being studed to convert biomass, but it is still too early to say which ones will be the most useful (*64*). Although there is no current, effective one-step method for converting raw lignocellulose to finished products, progress is being made. The firm KiOR (Pasadena, TX) recently demonstrated a one-step procedure for transforming cellulose into 5-hydroxymethylfurfural (HMF), which is a versatile biomass "platform" chemical for the production of solvents, fuels, and monomers for polymer production (*64*). Furthermore, increasing investments in the sugar−ethanol industry could facilitate the contruction of the physical infrastructure, and associated technologies that could also be used for the production of bioproducts (*3*). Biotechnology processes are particularly suited for the transformation of natural feedstock from sugar crops into the necessary sugars and building blocks of secondary bioproducts, and bioethanol itself can also be used as a platform chemical (*3*).

However, at the moment there are few budding entrepreneurs in the sugar industry taking advantage of the advances in process conversion technologies driving the biobased products sector (*3*).

Overall Future Outlook

In many areas of the world, particularly in Europe, there is currently a rapid diversification of the sugar and sugar−ethanol industries into "sugar processing industries" that are deeply involved in the maximization of sugarcane and sugar beet biomass (*65*), and more areas are expected to diversify for sustainability in the future. Furthermore, it is expected that "sugar" and "sugar−ethanol" companies, just like many other chemical companies, will be more and more eager to become greener (*66*) as they realize that they can reduce pollution and increase profits simultaneously (*67*). Companies will want to be able to select greener starting materials and use cleaner chemical processes to make environmentally preferred products (*66*).

Sustainability of the sugar and sugar ethanol industries should be viewed as a continuous improvement journey (*1*). Behavior change and education will be linchpins in effective sustainability programs. Traditionally, chemical/food process development has focused on economic criteria, but additional criteria for sustainability have become and will continue to be increasingly important and integrated into decision making processes (*68*). Assessment tools, standards, and enhanced metrics to measure "green, greener, or greenest" are being developed to achieve this tool in the U.S. (*66*). Ecological or environmental sustainability, one of the three pillars of sustainability (Figure 2) can be examined using Life Cycle Assessment (LCA) (*66*). This can be applied to new processes for converting sugar biomass. Furthermore, for sustainability of the sugar and sugar−ethanol industries, there will be a need for new analytical methods and standards in ethanol manufacture and for areas of grower payment with new biomass crops.

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Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

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