CHAPTER 1

The sugarcane industry, biofuel, and bioproduct perspectives

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1.1 Sugarcane – a global bioindustrial crop

Sugar (or more specifically sucrose) is one of the major food carbohydrate energy sources in the world. It is used as a sweetener, preservative, and colorant in baked and processed foods and beverages and is one of lowest cost energy sources for human metabolism.

On an industrial scale, sucrose is produced from two major crops – sugarcane, grown in tropical and subtropical regions of the world, and sugar beet, grown in more temperate climates. Sugarcane, however, accounts for the vast majority of global sugar production.

For much of the history of sugarcane production, sugar was a scarce and highly valued commodity. Sugarcane processing focused on extracting sucrose as efficiently as possible for the lucrative markets in the United Kingdom and Europe. The potential for the production of alternative products from sugarcane, however, has long been recognized. The key process by-products including bagasse, molasses, mud, and ash have all been investigated as a basis for the production of alternative products (Rao 1997, Taupier and Bugallo 2000).

Sugarcane is believed to have originated in southern Asia, and migrated in several waves following trade routes through the Pacific to Oceania and Hawaii and through India into Europe. Sugarcane was introduced and spread through the Americas following the expansion by British, Spanish, and Portuguese colonies in the 15th and 16th centuries (Barnes 1964).

While various methods of juice extraction and sugar production have been used over centuries to produce sugar, substantial innovations in sugar chemistry and processing technologies throughout the 18th and 19th centuries have formed the basis of modern sugar production methods (Bruhns *et al.* 1998). Dramatic improvements in processing efficiency, sugar quality, and automation and control characterized sugar processing throughout the 20th century.

While the production of alcoholic liquors from sugarcane juice and molasses has been known since ancient times, the production of rum has been associated with industrial sugar production since the introduction of sugarcane to the Caribbean in the 17th century. More recently, further coproducts started being produced including paper products, cardboard, compressed fiber board, and furfural from bagasse; ethanol, butanol, acetone, and acetates from molasses; and cane wax extracted from filter mud (Barnes 1964).

Perhaps the most significant development in sugarcane coproducts, however, occurred in 1975 when the Brazilian Government established the National Alcohol Program (the ProÁlcool program) in response to high oil prices and increasing costs of oil imports to Brazil. This program established a large domestic demand for ethanol, which resulted in the rapid expansion of the sugarcane industry in Brazil, enhancing technical capability, increasing the scale of factories, and lowering production costs of sugar and ethanol (Bajay *et al.* 2002).

The impact on global sugar and ethanol markets of ProÁlcool was profound, and this impact is still being felt today with Brazil being the undisputed global powerhouse of sugarcane production. The ProÁlcool program demonstrated the viability of sugarcane as a truly industrial crop, not just for food markets but also as a large-scale feedstock for the coproduction of energy products in integrated factories.

The period of the 1980s and 1990s saw sustained periods of low world sugar prices, in part the result of lower crude oil prices and increased Brazilian sugar exports, and increasing electricity prices in many countries. These factors focused the attention of the sugar industry on diversification opportunities and, in particular, the utilization of the surplus energy from bagasse to produce electricity for export into electrical distribution networks.

The past two decades have seen the emergence into the public consciousness of global challenges of climate change and increasing crude oil prices. Both these factors have enhanced human desires to find more renewable feedstocks for fuels, chemicals, and other products currently manufactured from fossil-based resources leading to direct consumer demand for more sustainable consumer products.

At the same time, human achievements and growth in our understanding of biotechnology have resulted in a suite of new tools that allow us to more readily convert renewable feedstocks into everyday products.

Sugarcane is widely acknowledged to be one of the best feedstocks for early-stage and large-scale commercialization of biomass into biofuels and bioproducts. As such, the sugarcane industry, with its abundant agricultural resource, is poised to benefit as a key participant in the growth of biofuel and bioproduct industries throughout the 21st century.

Figure 1.1 Leading sugarcane-producing countries (FAO 2015).

1.2 The global sugarcane industry

In 2013, more than 1.9 billion tons of sugarcane was grown globally at an average yield of 70.9 t/ha dominated by production in Brazil and India. Sugar beet production in 2013 was 247 million tons at an average yield of 56.4 t/ha (FAO 2015). The leading sugarcane-producing countries are shown in Figure 1.1.

Sugarcane is the largest agricultural crop by volume globally and the fifth largest by value with a production value in 2012 of US\$103.5 billion (FAO 2015).

The principal use of sugarcane throughout the world is for crystal sugar production for human consumption. In several countries, including Brazil, a sizable portion of the crop is also used for ethanol production from both sugarcane juice and molasses. Many other countries produce lesser quantities of ethanol from sugarcane juice or molasses.

Over the past decade, global sugarcane production has increased by 35%, driven by a doubling in sugarcane production in Brazil (FAO 2015). This increased sugarcane production has resulted in both increased crystal sugar production and increased ethanol production, and has had a significant impact on the world price of raw sugar. Land-use change enabling this global expansion of sugarcane production has both direct and indirect sustainability implications, and the factors relating to these implications are diverse and complex (Martinelli and Filoso 2008, Sparovek *et al.* 2009, Martinelli *et al.* 2010).

1.2.1 Sugarcane

Sugarcane is a C4 monocotyledonous perennial grass grown in tropical and sub-tropical regions of the world. Modern sugarcane varieties are complex hybrids derived through intensive selective breeding between the species *Saccharum officinarum* and *Saccharum spontaneum* (Cox *et al.* 2000).

Globally, the 1.9 billion tons of sugarcane produced annually is grown on about 26.9 million hectares (FAO 2015) in tropical and subtropical regions. Modern sugarcane varieties are capable of producing more than 55 t/ha/y of biomass (dry weight). The development of high biomass sugarcane (often referred to as energy cane) has the potential to significantly increase the amount of biomass available.

1.2.2 Sugarcane harvesting and transport

Sugarcane harvesting and transport practices vary around the world, principally depending upon the degree of mechanization of the process. Sugarcane may be burnt before harvesting or cut in a green state without burning. The burning of sugarcane is becoming less prevalent with the introduction and enforcement of environmental air quality guidelines and this is increasing the amount of sugarcane leaf material available for coproducts.

In some countries, hand cutting of sugarcane is still widely practiced, although this has been completely replaced by mechanical harvesting in many countries. The transition to mechanized harvesting has often been driven by the difficulty in attracting labor to the very physically demanding work of hand cutting. This transition has not been without significant challenges in ensuring the delivery of both the optimum sugarcane weight and a quality product low in dirt, leaves, and low-sucrose sugarcane tops, which are collectively referred to as extraneous matter.

Traditional sugarcane-harvesting processes cut the stalk around ground level and discard tops and leaf materials. Only the clean stalk (either as a whole stalk or cut into billets) is transported into the factory for the extraction of the juice and production of sugar. Tops and leaf material separated in harvesting (trash) are generally left in the field to decompose, acting as mulch and providing organic matter and nutrient for the soil, or raked and burnt depending upon farming practices.

Some proportion of this leaf material is of value in the agricultural system, improving the soil condition. The remainder of this extraneous matter is potentially available as a feedstock for biomass value-adding processes such as bioethanol production. The impacts of harvesting and transporting extraneous matter on the sugar milling process, and the economics of the industry, are complex and integrated modeling approaches have been developed to analyze these effects (Thorburn *et al.* 2006).

Transport of sugarcane to the factory in a timely manner is important to ensure that little sucrose is lost through degradation processes. Not only is this a requirement to ensure maximum recovery of the sugar product, but a significant presence of one of the key degradation products, dextran, has a major impact on sugar quality. Minimizing the formation of this polysaccharide is crucial to efficient sugar production.

In order to maximize the availability of biomass for cogeneration or coproducts production, some movement has been made toward whole-of-crop harvesting. In this harvesting approach, the entire crop including the field trash may be collected and transported to the mill. Ideally, this trash is separated before processing, as there are significant efficiency, sugar recovery, and sugar quality challenges associated with processing sugarcane trash in a conventional sugar factory.

1.2.3 The raw sugar production process

Sugarcane is processed in factories generally located close to sugarcane farming areas to minimize the cost of sugarcane transportation. The factories are constructed to crush the sugarcane to extract the juice and produce non-food-grade raw sugar as the primary product. Raw sugar from these factories is generally transported to sugar refineries where the sugar is further decolorized and purified to produce the high-quality white “refined” sugar that is used as table sugar and in industrial sugar applications.

Sugarcane factories do not typically operate year round, but only during the period in which sugarcane harvesting is done. This period, which varies throughout the world from around 5 to 9 months, is largely determined by climate and economic factors associated with the period of peak sugar content of the sugarcane.

In the raw sugar production process (Figure 1.2), sugarcane is first shredded to produce a fibrous material and the sugarcane juice extracted from the fiber through a process of milling and/or diffusion. Water is used to assist in washing the sugar from the fiber. The fibrous residue of this process is known as bagasse, and this bagasse is burnt in suspension in bagasse-fired water tube boilers to produce steam. The steam is used to provide energy to drive mill machinery, to produce electricity in turbo-alternators, and to provide heat for the process. The quantity of ash residue from the combustion process, known as boiler ash, varies depending upon the incoming dirt levels of the sugarcane.

The sugarcane juice is heated, limed, and clarified to separate the dirt and other insoluble impurities from the juice. The clean juice, generally known as clarified juice (CJ) or evaporator supply juice (ESJ), is fed into multiple effect vacuum evaporators where the juice is concentrated to around 65–70 brix to produce a concentrated syrup. The syrup is then passed to the panstage where the sugar crystallization occurs in a series of product and recovery sugar strikes.

High-grade (product) sugar from the panstage is centrifuged to produce sugar crystals of the target polarization and the molasses from these centrifugals is recycled to the panstage for further processing. The wet sugar from the centrifugals is passed to the sugar drier that dries the sugar to the target moisture specification, and this product is shipped to a refinery for further decolorization and impurity removal.

Figure 1.2 Typical schematic of the raw sugar production process.

Low-grade massecuite from the panstage is further processed to recover as much of the remaining sugar as possible from the molasses. This involves a process of cooling crystallization of the low-grade massecuite, followed by centrifugation to separate the recovered sugar from the final molasses. The quantity of final molasses produced depends on the quantity and types of impurities present in the sugarcane but is generally around 3–5% (w/w) of the sugarcane processed.

1.2.4 The refined sugar production process

The process for the conversion of raw sugar to refined sugar (Figure 1.3) is principally designed to achieve decolorization to a desired product specification. A series of processes are used to remove impurities while maximizing the yield of refined sugar. Several processing options exist and the number of decolorization stages required is determined by the purity and color of the initial sugar and the required color standard of the refined sugar product.

In the typical refined sugar process, raw sugar is initially processed through an affination station in which the raw sugar is mixed with affination centrifugal syrup (known as raw wash) and centrifuged to remove impurities contained in the highly colored molasses layer surrounding the sugar crystal. After the affination station, the affined sugar is remelted using water and steam to create melt liquor.

The melt liquor is processed through a primary decolorization stage using either a carbonatation process or a phosphatation clarification process. In carbonatation, the melt liquor is limed to a high pH, and carbon dioxide is bubbled through the liquor in a carbonatation column. The resultant calcium carbonate precipitate that is formed in this process removes impurities, and this precipitate is then filtered from the clarified liquor. In the phosphatation process, the melt liquor undergoes a clarification process with the addition of lime and phosphoric acid. In this case, the calcium phosphate complex adsorbs impurities, and the precipitate is skimmed off the surface of a flotation clarifier.

The clarified liquor then enters the second major decolorization process, and again there are several process options. These options include the use of activated carbon or ion-exchange resins to adsorb impurities from the clarified liquor. Both processes are highly effective at color removal from clarified liquor and the processes generate fine liquor suitable for crystallization.

The final stage of the refinery process is crystallization of the fine liquor to produce refined sugar massecuite, which is then centrifuged to separate the refined sugar crystals from the refined molasses. Several refined sugar strikes can be boiled and the number of product strikes is determined by the color specification of the product sugar. The refined sugar is dried and packaged for transport to retail and industrial customers.

Figure 1.3 Schematic of a typical refined sugar production process showing phosphatation clarification and ion exchange resin decolorization processes.

1.2.5 The sugar market

While raw sugar physically flows from raw sugar manufacturers to refineries, the price of sugar is generally determined with reference to a futures price and a basis price. The futures market allows for price discovery in a transparent market and provides risk management tools for sugar suppliers and purchasers. The basis price accounts for variation in the sugar quality between producers and freight costs differentials between sugars of varying countries of origin.

Raw sugar futures and options on futures are traded globally through the Intercontinental Exchange (known as ICE Futures US), which also trades futures of other soft commodities including cocoa, frozen concentrated orange juice, and cotton. Internationally, raw sugar is traded with reference to the Sugar No. 11 contract (US c/lb), which is for the physical delivery of lots of 112,000 lb of raw cane sugar, free on board the receiver's vessel at a port within the country of origin (Intercontinental Exchange Inc 2012).

There is a separate futures contract (Sugar No. 16) for the physical delivery of cane sugar of the United States or duty-free origin into US destinations. This is the result of the high import tariffs into the United States, which create a distinct market for US destination sugar and typically trades 35–50% higher than the Sugar No. 11 price (Intercontinental Exchange Inc 2012).

White sugar futures and options on futures are traded through the NYSE Euronext London International Financial Futures Exchange (LIFFE) White Sugar Futures Contract. This contract (in US dollars per ton) is for the delivery of 50 tonnes of white or refined beet or cane crystal sugar with a minimum polarization of 99.8° and maximum color of 45 ICUMSA units at the time of delivery to the vessel in the port of origin (NYSE Euronext 2013).

The raw sugar (ICE Futures US Sugar No. 11) to white sugar (LIFFE White Sugar Futures) differential is typically between 2 and 4.5 US c/lb (Intercontinental Exchange Inc 2012).

In a highly volatile market, the raw and white sugar futures markets allow sugar producers and their customers to manage price and currency risks using sophisticated tools in a transparent market. For raw sugar producers, this ability to manage price risk is particularly important given the inherent production risks associated with weather, pests, and diseases experienced in agricultural systems. Despite these markets, however, many sugarcane-processing factories are highly exposed to the revenue generated from sugar. This has led producers to seek alternative revenue streams to produce a more diversified revenue base from sugarcane.

1.3 Why biofuels and bioproducts?

1.3.1 The search for new revenue

Sucrose accounts for about 40% of the dry matter produced by the sugarcane plant but for conventional sugarcane factories producing raw sugar as the

primary product, raw sugar revenue accounts for more than 95% of the total revenue. Profitability in these factories is directly linked to the prevailing price of sugar on the volatile global market and the ability of the factory to limit production costs. For this reason, there is a strong interest among the global sugar community to diversify the revenue streams from sugarcane.

The process of revenue diversification seeks to create additional revenue streams such that there are multiple revenue streams contributing in a substantive way to the overall profitability of the facility. Ideally, at least some of these additional revenue streams have price profiles that are countercyclical to sugar. In this way, a downturn in the market price of one product has a lower impact on profitability resulting in less volatile revenue base. This can directly impact the investment attractiveness for current and potential shareholders, a more stable sugarcane price for suppliers, and better access to debt and equity markets at a lower price.

1.3.2 Sugar, ethanol, and cogeneration

The most common diversification strategies for sugarcane industries globally are for the coproduction of ethanol and large-scale cogeneration.

In diversifying into ethanol production, a portion of the sugarcane juice or molasses is directed to a distillery producing ethanol from the sugars contained in that material. For the utilization of sugarcane juice, A molasses or B molasses for the production of ethanol, there is a decrease in crystal sugar production and hence sugar revenue. The utilization of the C or final molasses for ethanol production does not come at the expense of crystal sugar production but much smaller ethanol production quantities can be achieved.

In sugarcane factories, bagasse is burnt to produce heat and power for the process. There is, however, much more energy in bagasse than is required for the process and, historically, sugarcane factories and combustion equipment were designed to be energy inefficient to ensure complete disposal of the bagasse, which had little value for alternate uses.

Increasing electricity prices, carbon pricing mechanisms, and renewable energy incentive schemes in many countries have resulted in a greater focus on increasing the energy efficiency of the sugar production process and equipment to produce large amounts of surplus electricity. This electricity can be fed into local transmission or distribution networks to provide renewable electricity to the local community and local industries.

The electricity that can be produced from bagasse can be increased by the utilization of other supplementary fiber sources including sugarcane trash or other local fiber crops.

While the technology for producing electricity from bagasse via combustion in water tube boilers and steam-driven turbo-alternators is well established, the potential revenue able to be generated from electricity sales (even including green credits) is quite moderate. With the fiber proportion of sugarcane

(including trash) being about two-thirds of the total above-ground component of the sugarcane crop (dry matter basis), there is significant interest in turning this high-volume, low-value resource into higher value products.

1.3.3 Fiber-based biofuels and bioproducts

Bagasse is an attractive feedstock for the production of fiber-based products. Bagasse has been used to commercially produce energy products (electricity via combustion or gasification), fuels, fiber products (paper and carton board), structural building materials, animal feed products, and chemicals such as furfural.

While the quality of many of these products is high, few of these products (other than electricity via combustion) are being produced in large quantities globally. One of the key challenges is for bagasse to compete with the best alternative feedstocks for the corresponding products, such as *Eucalypt* pulp for paper products and crude oil for industrial chemicals. Ensuring the availability of surplus bagasse in sufficient quantities for a world-scale chemicals or other manufacturing plant can also be a challenge and must be considered when entering competitive markets.

The rapid improvements in technology for the production of bioproducts is driving down the cost of production and decreasing the economically viable scale of production facilities. Further improvements in technology over the coming decade are expected to further enhance the opportunities for global sugar industries to add value to bagasse.

1.3.4 Climate change and renewable products

In 2006, the Stern Review on the Economics of Climate Change (Stern 2006) concluded that the scientific evidence on climate change is overwhelming, a serious and urgent issue and that the benefits of strong, early action considerably outweigh the costs of action. Independent reviews from many sources now recognize the majority scientific opinion that the climate is changing as a result of anthropogenic greenhouse gas emissions (Stern 2006, IPCC 2007, Garnaut 2008, The Royal Society 2008) and that the energy future we are creating is unsustainable (IEA 2006).

In general, these reports conclude that it is economically advantageous to undertake early action, and that deep cuts in carbon emissions in the first half of the 21st century are not only essential but achievable and affordable. It is generally recognized that there is no single solution for the challenges that climate change will bring through the 21st century and beyond, and that multiple strategies are required to both reduce carbon emissions and to adapt to the climate change effects that will inevitably occur.

The production of biofuels and bioproducts from renewable feedstocks such as sugarcane bagasse rather than equivalent products from nonrenewable fossil-based feedstocks is one path to reducing the intensity of emissions in modern human society. This provides a compelling incentive for increased

government investment in research and development that aims to fast-track the commercial release of biobased products and their broad-scale manufacture. The success of the Brazilian sugarcane ethanol industry and the US corn ethanol industry are good examples of how government policy can drive rapid change in investment in biobased technologies and drive down the cost for new capital investment.

1.3.5 New industries for sustainable regional communities

Many countries are becoming increasingly concerned with ensuring the security of their future energy resources and seeking to ensure continued scope for a proportion of domestic production. Renewable energy technologies have the potential to play a significant role in enhancing energy security (IEA 2007) through diversifying energy sources.

In addition, domestic production of biofuels reduces (to some degree) exposure to the price volatility in international energy markets, stimulates rural development, creates jobs, and saves foreign exchange (Kojima and Johnson 2005).

As an agricultural industry, the sugarcane industry is regionally based and central to the economic viability of rural and regional communities. The industry provides employment, economic growth, development, and in many cases essential services to the local communities in which they exist. As sugarcane is a rapidly perishable product, sugarcane-processing infrastructure must be located close to the sugarcane-growing region which ensures the ongoing regional nature of the industry.

The conversion of bagasse into biofuels and bioproducts offers the opportunity to significantly increase the value from sugarcane supplementing the revenue from sugar. Bagasse to bioproducts converts the lowest value component of the crop, the fiber component, into revenue sources that in the future could be at least as valuable, or potentially more valuable, than sucrose.

The development of new biofuel and bioproduct industries throughout regional sugarcane growing areas will, therefore, enhance regional development, provide employment opportunities in construction and operational phases, and provide revenue that will flow back through the communities to retail, services, and support industries. This offers the opportunity to reinvigorate rural and regional communities based around low-carbon industries and enhance economic and social sustainability of these communities.

1.4 Sugarcane biorefinery perspectives

1.4.1 The sugarcane biorefinery

The production of multiple coproducts from sugarcane biomass in integrated processing facilities is known as biorefining, and these facilities can be considered sugarcane biorefineries. Several assessments of sugarcane biorefineries have

been previously described (Godshall 2005, Pye 2005, Edye *et al.* 2006, Peterson 2006, Erickson 2007, Day *et al.* 2008).

Sugarcane bagasse is widely considered to be one of the best feedstocks for early-stage commercialization of biorefining technologies. Sugarcane bagasse has many key advantages as a biorefinery feedstock including the following (O'Hara *et al.* 2013):

1. Sugarcane is a highly efficient C4 photosynthetic crop producing high yields of biomass on an annual basis.
2. The sugarcane resource is massive and globally distributed.
3. Sugarcane is an established industrial crop with well-understood farming practices, pest and disease profiles, and well-established and sophisticated varietal development programs.
4. In terms of potential economic value, the biomass component of the crop (bagasse and trash) is vastly underutilized.
5. The major biomass residue from the crop (bagasse) is already at a centralized processing facility (the sugarcane factory).

As a result, sugarcane bagasse has a much lower feedstock risk profile and often a lower feedstock price than many other potential biorefinery feedstocks. The commercialization of any new biorefining technology is subject to significant technical and commercial risk, and the ability to reduce feedstock supply cost and risk is a key advantage of sugarcane bagasse as a biorefinery feedstock.

In centralized infrastructure, sugarcane factories process sugarcane into products. For this purpose, they require essential infrastructure including boilers, electrical generation and distribution equipment, cooling water, effluent treatment, maintenance, and other support services.

In biorefineries, sugarcane factories not only integrate sugarcane processing, sugar production, and renewable energy production, but in addition produce biotechnology products from biomass. Further to the emergence of sugarcane biorefineries is the opportunity for these facilities to be the catalyst for new regional renewable energy and biotechnology hubs attracting related industries and innovation enterprises able to make use of the central infrastructure, energy availability, and coproduct streams as inputs to their processes (Figure 1.4).

Most organic chemicals produced from fossil-based resources can also be produced from biomass (Bridgwater *et al.* 2010). Several studies have assessed the range of potential chemical products from biomass and more than 300 potential products have been identified (Werpy *et al.* 2004, Bridgwater *et al.* 2010).

Products that are able to be produced in biorefineries include alcohols (methanol, ethanol, and butanol), macromolecules, and other compounds derived from lignin, specialty sugars, organic acids, fermentation products, and energy products including biodiesel, hydrogen, gasoline, and diesel replacements (Table 1.1).

Figure 1.4 Conceptual model of a sugarcane biorefinery with the sugarcane factory as a hub for renewable energy and bioproduct technologies and services (O'Hara *et al.* 2013).

Table 1.1 Potential chemicals and bioproducts from biomass (O'Hara *et al.* 2013).

Products from biomass (Bridgwater <i>et al.</i> 2010)	Chemicals from sugars (Werpy <i>et al.</i> 2004)	Chemicals from lignin (Holladay <i>et al.</i> 2007)	Chemicals from syngas (Spath and Dayton 2003)
1,2-Propanediol	1,4-Succinic, fumaric and malic acids	Macromolecules	Hydrogen
Epichlorohydrin	2,5-Furan	Carbon fiber	Ammonia
Lactic acid	dicarboxylic acid	Polymer modifiers	Methanol and derivatives
Diesel	3-Hydroxy propionic acid	Thermoset resins	<i>di</i> -methyl ether (DME)
Gasoline	Aspartic acid	Aromatic chemicals	Acetic acid
Kerosene	Glucaric acid	BTX (benzene, toluene, xylene) derivatives	Formaldehyde
Ethanol	Glutamic acid	Phenol	Methyl <i>tert</i> -butyl ether (MTBE)
Methanol	Itaconic acid	Lignin monomers	Methanol to olefins
DME	Levulinic acid	Propylphenol	Methanol to gasoline
Char	3-Hydroxybutyrolactone	Eugenol	Ethanol
Wood pellets	Alcohols (e.g., glycerol, sorbitol, xylitol/arabinitol)	Syringol, Oxidized lignin monomers	Mixed higher alcohols
Animal feed		Syringaldehyde	Oxosynthesis products
1,3-Propanediol		Vanillin	(C ₃ –C ₁₅ aldehydes)
Carbon dioxide		Vanillic acid	Isosynthesis products (isobutene, isobutane)

1.4.2 The sustainability imperative

While there is significant consumer demand for renewable and sustainable products that demonstrate green credentials, consumers have generally shown an unwillingness to pay more for green products than their fossil-fuel-derived counterparts. It is critical, therefore, that biofuel and bioproduct technologies continue to develop to be cost-competitive with their fossil fuel equivalents.

However, it is critical as we move toward large-scale change from fossil-based products to biobased products that the industry demonstrates its advantage in environmental sustainability over alternative production systems.

The production of sugarcane-based biofuels and bioproducts has the potential to result in both positive and negative environmental outcomes. Indeed, these outcomes may vary based on the location or even the way the technology is implemented.

Sugarcane production requires the use of land, water, fertilizer, agricultural chemicals, fuels, and other inputs. The implications of land-use change, which can impact directly on forestation, biodiversity, food crop production, and competition for constrained resources, can have profound implications for regional and global communities. The challenges associated with measuring and assessing indirect land-use change are very complex but important.

Sugar production also has potential environmental impacts associated with emissions from fossil fuel combustion, chemicals utilization, and waste water treatment and discharge.

However, sugarcane also contributes to positive environmental outcomes through the production of electricity, bioproducts, and fuels from a renewable feedstock. The growth of sugarcane fixes carbon dioxide into plant biomass resulting in sugarcane being a contributor to the low-carbon manufacturing economy.

The assessment of the environmental credentials of production systems is undertaken through life cycle assessment (LCA). The license to operate for future production systems will require demonstration of their environmental credentials using these tools.

LCA considers the production system from cradle-to-grave within defined system boundaries. Many LCA techniques consider not just the environmental impacts but social impacts as well. Carbon footprint analysis is one of the critical components of LCA but many other factors are also identified as important in the development of global standards and assessment methodologies, such as ISO 14040:2006 and the Roundtable for Sustainable Biomaterials (RSB) standards.

Public debate throughout the past several years has also focused on the potential for bioproduct systems (in particular biofuels) to negatively impact on food production with particular implications for food prices on the poorest people in society. While this is a potential consequence of certain biofuels and bioproducts systems, the challenge for human society is to deliver both food and energy in an adequate, sustainable, and affordable manner. Modern human society is critically

dependent upon both food and energy, and in fact the food and energy systems are inextricably linked with around 30% of total primary energy consumption in the “paddock-to-plate” food supply chain (FAO 2011).

In today’s global society, the public perception of the economic, social, and environmental sustainability of biofuels and bioproducts from sugarcane will be influenced as much or more by international reputation than regional sugarcane production standards. It is critically important, therefore, that all sugarcane industries around the world contribute to continual improvement in sustainability of their domestic production systems to ensure their future license to operate and ensure that sugarcane continues to be considered by the international community as a highly desired feedstock for the production of biofuels and bioproducts.

1.4.3 Future developments in biotechnology for sugarcane biorefineries

Biotechnology is causing rapid changes in many areas of human endeavor including medicine, health, environmental remediation, agriculture, and manufacturing. This change is leading to significant increases in yield and productivity of agricultural crops and biotechnology processes and hence a reduction in the cost of bioproducts. A good example of this is the dramatic decrease in cellulase enzyme cost that has been reported over the last decade (Stephen *et al.* 2012).

Biotechnology offers significant opportunities for the future development of sugarcane biorefineries. These future developments will improve productivity and yields of sugarcane feedstocks and biorefinery products and further improve the sustainability outcomes. Most remarkable are the opportunities in agricultural biotechnology to improve sugarcane as a feedstock and industrial biotechnology to improve the biorefinery process.

While sugarcane is inherently a good feedstock for biorefineries, biotechnology offers the opportunity to improve agricultural yields with reduced crop inputs. Key opportunities in agricultural biotechnology to improve sugarcane as a biorefinery feedstock include

- more biomass through increased sugarcane yields per hectare;
- increased sucrose and total fermentable sugar contents of sugarcane;
- improved sugarcane resilience to abiotic and biotic stresses including drought, salinity, frost, pest, and disease;
- modified sugarcane fiber composition or morphology targeted at more efficient processing (e.g., lower lignin contents or higher cellulose contents); and
- more value embedded in the sugarcane such as through the *in planta* production of proteins, enzymes, specialty sugars, chemicals, or plastics.

The growing field of industrial biotechnology also offers opportunities to enhance value-creation from sugarcane processing through

- cost-effective processes for creating value-added products from sucrose and fermentable sugars;

- the production of value-added products from sugarcane by-products including bagasse, trash, molasses, vinasse, and filter mud;
- increased focus on clean technology production processes reducing energy requirements and environmental impacts from sugarcane processing; and
- enhanced processes for wastewater treatment.

While the sugar production process is considered by many to be technologically mature, biotechnology will play an important role in the next generation of sugarcane production and sugar-processing improvements. In particular, biotechnology improvements will be necessary to ensure that sugarcane remains amongst the lowest cost feedstocks for biorefinery processes and that the profitability of the production of biofuels and bioproducts from sugarcane carbohydrates can match and exceed that of their current fossil fuel equivalents.

1.5 Concluding remarks

Sugarcane is an important global agricultural crop that has made a major contribution to the development of communities and nations throughout tropical and subtropical regions of the world over the past few centuries. It remains the fifth largest crop (by production volume) and is a major contributor to gross national product in many tropical countries.

Sugarcane has been principally used for the production of crystal sugar, although increasingly ethanol and cogeneration are contributing to total sugarcane revenue.

The production of biofuels and bioproducts offers significant opportunities to enhance the revenue from sugarcane and contribute to more economically, environmentally, and socially sustainable sugarcane production around the world. The transition of sugarcane-processing factories into biorefineries coproducing food, feed, biofuels, and bioproducts in integrated facilities will be one of the most important changes to impact the future viability of the industry. These changes will generate new industries for regional communities in low emission manufacturing technologies.

Biotechnology is poised to bring significant new developments that will further position sugarcane as a leading feedstock for new biorefinery industries. However, the sugarcane industry needs to place sustainability at the core of its operations and continue to build and reinforce its social license to operate.

Indeed, the ongoing social license to operate requires the sugarcane industry globally to further improve its triple bottom line performance, and the production of biofuels and bioproducts can assist in furthering this aim. This will assist in ensuring a vibrant and sustainable future for sugarcane production globally and place sugarcane production as a major contributor to sustainable human societies over the next century.

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