Muhammad Tahir Khan
Imtiaz Ahmed Khan *Editors*

Sugarcane Biofuels

Status, Potential, and Prospects of the Sweet Crop to Fuel the World

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Preface

Sugarcane is the world's largest crop with respect to total production and is cultivated in a wide range of tropical and subtropical climate. It is grown in more than a hundred countries of the world, mainly as a source of sugar. Nevertheless, sugarcane has recently been endorsed as a source of biofuel and bioenergy also, as its sucrose production can be diverted to ethanol production through first-generation route and its biomass can be utilized for engendering second-generation biofuels as well as bioenergy.

Ever-increasing energy demands of the world, diminishing reserves of fossil-based fuel resources, environmental pollution, and consequential economic disquiet have induced huge interests into renewable, sustainable, and environment-friendly sources of energy, such as sugarcane. Since the success of *ProAlcool* program in Brazil, one of the major questions in sugarcane and bioenergy research has been whether the same could be replicated in other cane-growing countries as well. This is the question which intrigued us to compile this book. Sugarcane exhibits all the major characteristics of a promising bioenergy crop including high biomass yield, C4 photosynthetic system, perennial nature, and ratooning ability. Apart from Brazil, Thailand and Colombia are also significantly exploiting this energy source. However, other sugarcane producers including India, China, Pakistan, Mexico, Australia, Indonesia, and the United States could also augment the contribution of this incredible crop toward their fuel and energy sector.

This book analyzes the significance, applications, achievements, and future avenues of biofuels and bioenergy production from sugarcane in top cane-growing countries around the globe. Moreover, we also evaluate the barriers and areas of improvement for targeting efficient, sustainable, and cost-effective biofuels from sugarcane to meet the world's energy needs and combat climate change. Despite economic and environmental benefits, there are challenges both common and unique to each of the cane producers. The agroclimatic conditions, land resources, water availability, planting conditions, and capacity of the sugar industry vary from country to country. There is a considerable knowledge gap on these issues which have been analyzed in this book in order to understand the role sugarcane can play as an energy resource.

The book has been divided into three major sections. Part I summarizes various possible routes of energy extraction from cane. Part II deals with the current status and future prospects of sugarcane's role in bioenergy production in major cane-growing countries, while Part III covers the industrial and technological aspects, sustainability issues, and future avenues of energy engenderment from sugarcane. Recent developments in energy cane, transgenics and genome editing, second-generation bioethanol, and biorefinery concept have also been presented as such advances will play a preponderant role in energy independence of various countries in the future, without impacting the food security.

We are extremely thankful to all the contributors for sharing their erudition and for bearing with us during the rigorous editing and review process. We also want to thank the authors for enduring editorial suggestions to produce this venture. Moreover, we acknowledge the support received from friends and our family members to make this happen. Finally, we also wish to express our gratitude to Springer International Publishers for cooperation and feedback during the editing of this book.

Tandojam, Pakistan

Muhammad Tahir Khan
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Part I
Sugarcane as a Bioenergy Crop

Chapter 1
Sugarcane as a Bioenergy Source

Ghulam Raza, Kazim Ali, Muhammad Aamir Hassan, Mudassar Ashraf, Muhammad Tahir Khan, and Imtiaz Ahmed Khan

1.1 World's Resources of Energy

There are two types of energy resources for the world's needs: primary and secondary. Primary sources are the main reservoirs from where the energy generates. These can be converted into secondary resources which can further be used as input for a system. Such energy resources could be renewable (consonants) and non-renewable (non-consonants) (Bokor 2016). Major types of non-renewable energy resources are coal, hydrocarbons (petroleum and natural gases), and nuclear (Fig. 1.1). Such resources have played important role to meet the world's energy requirements. Eighty-four percent of the global consumption is being fulfilled through such resources; therefore, they are depleting continuously at a rapid pace. It has been forecasted that fossil fuel reservoirs will not extend beyond half of this century given the increasing rate of their use (Carvalho-Netto et al. 2014). These sources also have various adverse effects on the environment and climate, and ultimately long-term implications on the globe. Climatic outcomes of the fossil fuels include global warming, smog, air pollution, and increase in atmospheric CO_2 (Bokor 2016).

In recent years, there has been a special research focus on exploration of alternative energy that could minimize or replace the fossil fuel usage (Waclawovsky et al. 2010). The most attractive alternate options are renewable energy resources such as solar, wind, hydropower, wave/tidal, geothermal, and bioenergy, as described in Fig. 1.1 (Bokor 2016). Among these renewable energy resources, bioenergy can be

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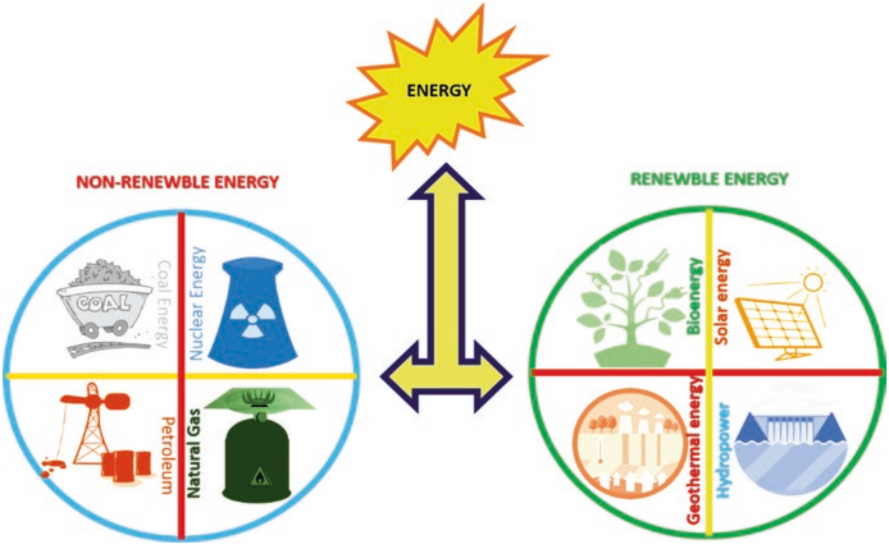

Fig. 1.1 Different sources of energy

produced from many available feedstocks to satisfy our increasing energy demands. Ample bioenergy production in a country can play significant role for secure, sustainable, and economically sound future by providing clean energy domestically, reducing oil imports, and creating jobs.

1.2 Bioenergy

Bioenergy is the energy produced from biological material (including plants, animals, and their by-products), called biomass. Bioenergy can be utilized to generate heat, electricity, and transportation fuels. In 2015, 10% of the total global energy consumption and 1.4% of global power generation were shared by bioenergy (International Renewable Energy Agency [IRENA] 2017). Globally, North America contributes maximum toward biofuel production (~50%) followed by South America and Europe, while contribution from other regions is very small. Apart from reducing dependency on fossils-based resources, utilization of bioenergy would also decrease the negative effects on environment by limiting the release of greenhouse gases (GHG). Considering socioeconomic and environmental benefits of renewable sources of energy, several countries are mandating the share of bioenergy in their national energy matrix.

Till now, many crops have been identified and others are being explored for marketable energy farming, for instance, corn, soybean, willow, and switch grass in the USA; rapeseed, wheat, sugar beet, and willow in Europe; palm oil and miscanthus in Southeast Asia; sorghum and cassava in China; and hemp in India (Cho 2018;

Davis et al. 2013). In broad spectrum, features of the most ideal bioenergy crop would be high dry matter production per unit area, small input costs, simple digestion, and low level of contaminants in the produce (McKendry 2002). Among various bioenergy options, sugarcane is one of the most efficient energy crops as it converts sunlight energy into stored chemical energy with huge efficiency. Sugarcane has C4 photosynthetic system which results in enormous biomass production per unit area (Tew and Cobill 2008; Furtado et al. 2014). It exceptionally fulfills all the basic requirements to serve as a potential energy source including excellent yields, low inputs for growth, less competition against food crops, and good processing efficiencies.

1.3 Economic Importance of Sugarcane in the World

Sugarcane is mainly a crop of tropical and subtropical regions, and it is being cultivated since pre-historic period. Being a source of 70% of world's sugar production, it is a very important cash crop for cane-growing countries. Sugarcane has a wide range of adaptability and is grown in more than 100 countries. Worldwide, it is grown on an area of 26.8 million ha, and its total production is ~1.9 billion tons with a fresh cane yield of 70.9 tons ha^{-1} (Hoang et al. 2015; FAOSTAT 2016). Gross production value of sugarcane is US$92.2 billion for the globe (FAOSTAT 2016). Sugarcane is source of a number of industrial products and by-products, which have transformed the local and international trade in many countries. Its production has played significant and dominant role in changing the economic and fiscal position of sugarcane-farming countries. From its domestication to date, sugarcane has remained an important crop and a role player for the betterment of socioeconomic status of growing regions.

1.4 Sugarcane: As an Agricultural Commodity

Sugarcane (*Saccharum officinarum* L.) is a perennial grass, classified as tribe *Andropogoneae*, family *Poaceae*, genus *Saccharum*, and species *officinarum* (Hodkinson et al. 2002). Commercial sugarcane is the cross of *Saccharum officinarum* with wild *Saccharum* spp., i.e., *S. spontaneum*, *S. robustum*, *S. barberi*, *S. sinense*, and *S. edule* (Talukdar et al. 2017). Previously commercial sugarcane was designated as *Saccharum officinarum*; however, *Saccharum* sp. hybrid has been adopted as the prioritized term to refer to commercial sugarcane (Tai and Miller 2001). Due to high pollen sterility, viable seed production is scarce, and therefore, it is grown through vegetative cuttings. Because of its vegetative mode of cultivation, sugarcane is among the plants which require great human intervention (Allsopp et al. 2000).

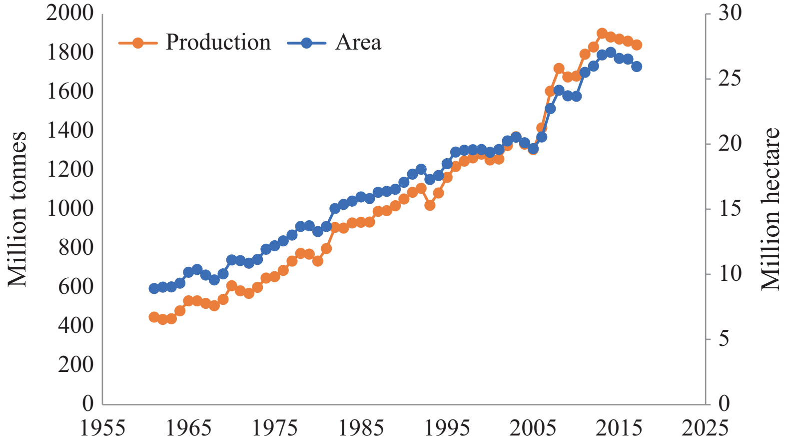

Fig. 1.2 Sugarcane area and production around the world over time (FAOSTAT 2017)

Sugarcane was identified as a cash crop in early ages of its farming (Price 1963). Being a crop of tropical region, it was mainly grown in the southern states of Americas initially and then spread to the USA (Hawaii, Louisiana, Florida, and Puerto Rico). Afterward, its production has continuously increased over time (Fig. 1.2) (FAOSTAT 2017; Ham et al. 2000; Hammond 1999; Price 1963, 1965). The primary use of sugarcane is to produce sucrose sugar; moreover, carbohydrates of sugarcane are employed as a preservative as well as bonbon agent for foods and in the manufacture of confectionary items and alcohol (Aoki et al. 2006; Wu and Birch 2007). Miller and Tai (1992) reported that more than 70% of the world's sugar demand is fulfilled through sugarcane, ranking it as the chief source of sugar supply to the world.

1.4.1 Origins and Distribution

Sugarcane is a C4 monocotyledonous plant. Cultivated sugarcane is an interspecific hybrid primarily evolved through crosses between *Saccharum officinarum* L. and *S. spontaneum* L. (Allen et al. 1997; Jeswiet 1929).

Saccharum officinarum produces high sucrose content; therefore, it is named as "noble cane." Nevertheless, it has poor attributes of tolerance against biotic and abiotic stresses. *S. officinarum* is premised as an outcome of introgression between *S. spontaneum*, *Erianthus arundinaceus*, and *Miscanthus sinensis* (Daniels and Roach 1987; Sreenivasan et al. 1987). Polynesia is contemplated to be the center of origin of *S. officinarum*. The species was later transported to Southeast Asia, Papua New Guinea, and Irian Jaya (Indonesia) in the late 1800s (Daniels and Roach 1987). Sugarcane is now grown in a wide range of altitudes covering more than 100

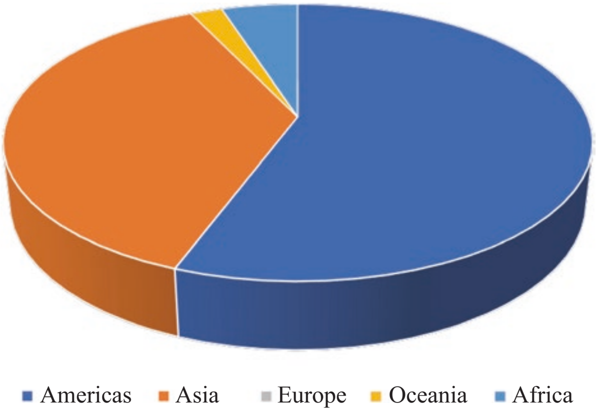

Fig. 1.3 Worldwide share of sugarcane production by different cane-growing regions (FAOSTAT 2017)

countries of tropics and temperate regions from latitude 80S to 40N (Fig. 1.3) (Daniels and Roach 1987; Tai and Miller 2001).

Sugarcane is a mainly cultivated for disaccharide sugar. Sugar production starts with juice extraction by crushing cane at the mills. The juice is then clarified at high temperature in the presence of lime [$Ca(OH)_2$], which forms complexes with phosphorus in the juice and precipitates as calcium phosphate, and allowed to settle down taking other impurities with it. Flocculants (substances added to solutions to produce woolly looking masses of particles which assist in settling down suspensions) are added to speed up this process (Mackintosh 2000).

1.4.2 Modern Commercial Hybrids

Breeding for sugarcane improvement has mainly emphasized on the sugar contents; however, now sugarcane is being recognized as an excellent source of fuel energy as well (Besse et al. 1997; Sreenivasan et al. 1987). Improvement in sucrose percentage along with maintaining tolerance against biotic and abiotic stresses has been achieved through a number of back-crosses to several different cultivars of *S. officinarum* (Bull and Glasziou 1979). Approximately 80% of the chromosomes in these commercial hybrid cultivars are derived from *S. officinarum* and 10% are from *S. spontaneum*, with remainder being chromosomes from the two species produced by the natural process of synapsis during meiosis (D'Hont et al. 1996).

D'Hont et al. (1996) and Sreenivasan et al. (1987) elaborated that for accumulation of more *S. officinarum* genome in genotypes, interspecific hybridization between *S. officinarum* and *S. spontaneum* resulted in triploid chromosome number ($2n + n = 100$ to 130). Commercial sugarcane spreads vegetatively; hence, it is highly heterozygous in nature (Kimbeng et al. 2001). Pollen sterility and uneven distribution of chromosomes during anaphase stage restrict selfing in sugarcane; therefore, pure lines do not exist (Milligan et al. 1990). Uneven chromosome pairing of sugarcane also results in aneuploidy and euploidy during chromosomal transmission (Tai and Miller 2001).

1.5 Sugarcane as a Bioenergy Crop: Advantages over Other Options

Industrial revolution of the seventeenth and eighteenth centuries resulted in escalation in petroleum prices. Consequently, high demands of fuels and the aims of curtailing petroleum usage pushed fuel industries to look for feasible substitutes including biofuels. Moreover, advances in fermentation technology and improvement in process efficiencies enhanced prospects for using crops for biofuels production.

Sugarcane, as a feedstock, has potential to become a major bioenergy source as it has highest yield per unit area among the agricultural commodities, thus offering possibility of excellent energy balance than other bioenergy options (Waclawovsky et al. 2010). As a C4 plant, sugarcane yields higher biomass than maize, miscanthus, and switch grass (Heaton et al. 2008). Its per hectare yield is also far greater than that of sugar beet, thus surpassing all other options in this context. High-yielding biofuel feedstocks are preferred as they offer less competition for the land to be used for food crops otherwise (Peskett et al. 2007).

Sugarcane and energy cane have good potential for cultivation on non-fertile agricultural lands as well (Waclawovsky et al. 2010). Furthermore, first-generation sugarcane bioethanol engenderment does not need expensive pretreatment steps, which are the major monetary barriers in case of other crops. Additionally, sugarcane already has a well-set milling industry established in many cane-growing countries of the world, most of which are developing nations—in urgent need of alternative energy sources.

Sugarcane industry is not only limited to sugar, ethanol, and bioelectricity production, but numerous other products can also be manufactured using the same feedstock hinting toward sustainability and cost-effectiveness of this industry, as biorefinery concept of sugarcane is rapidly evolving (Fig. 1.4). Moreover, the potential of sugarcane for its energy parameters has been widely unexplored yet, thus offering more likelihood of breakthroughs for any breeding program targeting the same. Even more, sugarcane feedstock can excellently deal with the food vs. fuel issues when its second-generation processing is matured, as second-generation route will be providing additional incentives in the form ethanol which won't offer any competition against sugar engenderment (Khan et al. 2017a). Hence, sugarcane is one of the most suitable options for bioenergy production.

Fig. 1.4 Different products and by-products from sugarcane

1.6 Deriving Biofuels and Bioenergy from Sugarcane: History, Status, Approaches, and Potential

Sugarcane's fibrous stalks are rich in sucrose, which is accumulated in its internodes. Sugarcane industry and distilleries extract this sugar and subject it to fermentation to generate ethanol (Talukdar et al. 2017). Cane-derived ethanol is being used as a first-generation biofuel predominately in Brazil, where half of the total crop is used to produce ethanol (Pessoa et al., 2005). Worldwide, sugarcane is source of 21 million m^3 ethanol (Renewable Energy Policy Network for the 21st Century 2016). Average sugarcane varieties yield 85–100 kg sugar and 35–45 kg molasses (as by-product) from 1 ton of cane biomass, whereas 22–25% ethanol recovery is obtained from molasses through fermentation (Sukumaran et al. 2017). About 80% of the world's molasses is used for alcohol production through biochemical process, whereas the remaining finds applications as animal feed. Bagasse, the other major by-product of sugarcane processing, is mainly used as a source of bioelectricity and also for paper, board, and xylitol production purposes (Wolf 2012).

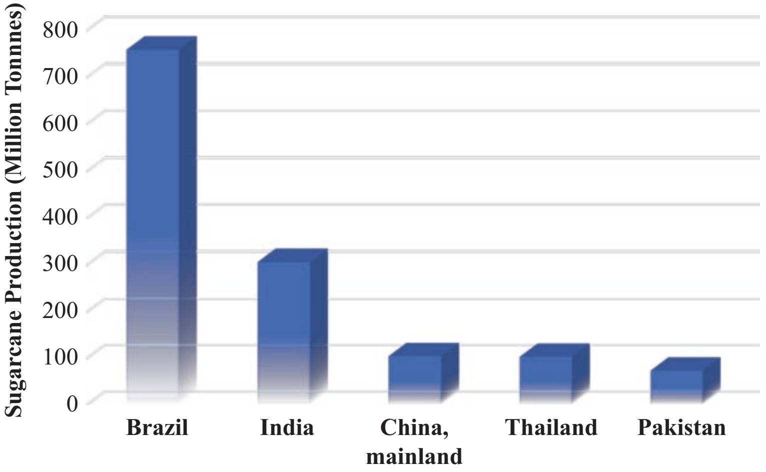

Fig. 1.5 Sugarcane production in top five cane-growing countries of the world

Sugarcane is being extensively used for biofuels production in Brazil, while the crop has significant unexplored potential for other cane-growing countries as well (Fig. 1.5). It has emerged as an excellent source of biofuels since the 1930s, when Brazil launched a policy requiring industrial-scale production of ethanol as an automobile fuel (Alagoas 2000). Brazil regularized the sugarcane production under the umbrella of the Institute of Sugar and Alcohol (Instituto do Açúcar e do Álcool). In 1973, first oil crisis drove the Brazilian administration to launch the *ProAlcool* program for realizing the possibilities of commercial and large-scale biofuel production from sugarcane. Through this program, the country launched a number of bioethanol units in existing sugarcane industry. The primary purpose was to generate ethanol for blending with gasoline in different ratios, for using as a biofuel in automobiles. In parallel, the automobile industry focused on modification of car engines, and the cars having ability to use bioethanol as fuel were introduced. After 2003, flex-fuel cars were developed in Brazil. Engines of these cars were modified to either completely replace gasoline or use a mixture of bioethanol and gasoline in any certain ratio. Presently, in Brazil, it is mandatory for gasoline business to mix at least 22% bioethanol.

Brazil also ranks at top globally in terms of efficiency of its biofuel sector. During 1980–1998, sugarcane culm yields improved from 73 to 90 tons ha^{-1} $year^{-1}$, sugar extraction efficiency increased from 90% to 96%, and fermentation output enhanced from 84% to 90.7%, whereas sugar conversion also reached 90%. During 2017–2018, Brazil produced 511 million tons of sugarcane and 26.7 billion liters of bioethanol (FAOSTAT 2016; STATISTA 2017). Xavier (2007) evaluated that ethanol produced from sugarcane accounts only 1% of the existing land in Brazil, and the current increase in sugarcane production for biofuels is not bulky enough to enlighten the shift of small farmers into deforested zones. Although efficiency of sugarcane crop and its processing industry is quite up to the mark, still, there is a gap for improvement of sugarcane productivity and industrial processing.

Sugarcane ethanol and biomass, an ample carbon-neutral renewable energy resource, offers a promising prospect as an alternative of non-renewable fuels (Lynd et al. 2008). Apart from vehicle fuels, Ragauskas et al. (2006) proposed that the combination of bioenergy crops and establishment of bioenergy industries would help in sustainable power production that may lead to a new industrial paradigm. This road map incited the launching of a number of biomass energy centers in different countries across the world.

Presently, first-generation bioethanol is being produced from sugarcane, which involves sucrose concentration and extraction from juice, followed by fermentation and distillation. This ethanol fraction corresponds to only a third of the cane energy, and the other plant residues correspond to the remaining two thirds. So, by utilizing bagasse, straw, trash, and tops, the other portion (66%) of sugarcane biomass, production of bioenergy from this crop can be enhanced. It has been predicted using simulation studies that reasonable outcomes could be achieved from sugarcane biomass for ethanol production through biochemical and/or thermochemical conversion methods (de Souza et al. 2014).

In the past, sugarcane research has been focused on the development of new sugarcane cultivars which could have high sucrose contents to generate more sugar and first-generation bioethanol. However, recently, focus has also been shifted to high-fiber/high-biomass "energy cane" varieties for the production of second-generation bioethanol (Landell and Bressiani 2008; Knoll et al. 2013). This type of cane varieties is endowed with two distinguishing agronomic traits, viz., high tillering capacity and excellent ratooning ability. Such cultivars are further classified into two types: Type I contains sugar >13% and has fiber content >17%, while Type II energy cane is exclusively developed for higher biomass and contains low sugar (<5%) and high fiber (>30%) (Tew and Cobill 2008). Energy cane also contains marginally higher lignin than the conventional type (Knoll et al. 2013). Moreover, total biomass and fiber contents of energy cane are also significantly higher, i.e., 138% and 235% more than the conventional cultivars, respectively (Matsuoka et al. 2012). Such cane type easily meets all the requirements of a renewable biomass resource (Matsuoka and Stolf 2012).

Based on sugar and fiber contents, energy cane has been grouped as a potential energy source (Matsuoka et al. 2014). Cultivation of energy cane varieties is expected to increase as the advanced methods to convert lignocellulosic biomass into bioethanol become available (Carvalho-Netto et al. 2014). Sugarcane growers may use marginal and less fertile land to produce lignocellulosic biomass by cultivating energy cane in the areas where conventional sugarcane cultivation is not feasible (Sandhu and Gilbert 2014). Recently, Matsuoka et al. (2014) reported that private breeding companies have developed both Type I and Type II energy canes in Brazil, which were proposed for expansion beyond tropical and subtropical areas due to their wide range of adaptability and tolerance to low temperature (Knoll et al. 2013; Van Antwerpen et al. 2013).

Sugarcane cell wall is the most important factor dictating the efficiency of second-generation cane biofuels production. On the basis of structure, chemical composition, and biosynthesis, the cell wall is divided into two types: (1) primary cell wall (PCW) and (2) secondary cell wall (SCW) (Carpita 1996). PCW is formed by the deposition of complex carbohydrates mainly cellulose, hemicellulose, and pectin (Cosgrove 2005). Cellulose and hemicellulose work as the bones of plants and are supported further by lignin and phenolic cross-linkages (Carpita 1996). Sugarcane SCW is made up of 50% cellulose, 25% lignin, and 25% hemicellulose (Loureiro et al. 2011). Production of second-generation bioethanol from plant biomass is not only linked with cellulose content, but also depends upon the cell wall quality. Buckeridge et al. (2010) obtained 40% increase in sugarcane-based bioethanol production by exploiting the potential energy in sugarcane cell wall. In this perspective, de Souza et al. (2014) indicated that distribution of carbon between non-structural carbohydrates (sucrose, glucose, fructose, and starch) and structural carbohydrates (cellulose, hemicelluloses, and pectin) is very important to determine an optimal balance between bioethanol-producing processes of first and second generations. The stability between structural (cell wall) and non-structural polysaccharides (typically consisting of sucrose and starch) varies among the feedstocks.

Significant variations exist in starch and sucrose contents of the cell wall among different crops and even within species and cultivars. It is an established fact that breeding for higher sucrose contents is strongly associated with the decline in cellulose content. Carbon distribution between non-structural and structural carbohydrates is generally controlled through the variations in metabolism of nucleotide sugars. However, the process involved in the completion of plant cells' fluxes between ADP and UDP-glucose is unclear (de Souza et al. 2014). The complex cell wall structure and biosynthetic processes of the cell wall polysaccharides indicate that it is not easy to take on the methods which could help in changing cell wall composition without affecting other biological systems or pathways (Pauly and Keegstra 2010). Yet, it has been discovered that sugarcane cell wall is composed of remarkably high magnitude of mixed-linkage β-glucan, which increases the possibility for improvement of sugarcane for higher bioenergy production (de Souza et al. 2013).

In 2013, detailed analysis of sugarcane cell wall was done using various techniques. Glycomic profiling was employed to determine the monosaccharide composition of sugarcane cell wall, while structural analysis of oligosaccharides was examined by hydrolysis with endo-glucanases and separation by liquid chromatography (de Souza et al. 2013). As mentioned earlier, major components of lignocellulosic substrate include cellulose (40–50%), hemicellulose (25–35%), and lignin (15–20%). Cellulose is a polymer of glucose and hemicellulose (consisting of xylose and arabinose), whereas lignin is a complex poly-aromatic compound. In sugarcane, cellulose contents of 43– 49% were found in dry biomass and energy cane varieties (Sanjuan et al. 2001; Kim and Day 2011), while in wood and forage grass, the contents are about 45% and 30%, respectively (Theander and Westerlund 1993; Smook 1992). Development of efficient cell wall digestion approaches is expected to enhance fuel and energy yields of sugarcane by manifolds.

1.7 Sugarcane Improvement for Bioenergy

There have been strenuous research efforts for genetic improvement of sugarcane (Hoang et al. 2015). In countries having mandated ethanol blends already, sugarcane crop has gained vital importance as a fuel source. However, its expansion as a bioenergy system has been slow due to less understanding of its physiological aspects of photosynthesis and intricate source-sink relationships. Two routes of fuel production are being exploited: the first one involves the conversion of sugar or molasses into ethanol, while the second one considers biomass conversion into ethanol—for ultimate blending with gasoline. It is anticipated that, in recent future, sugarcane will be extensively grown as a fuel feedstock also, rather than as a sugar crop only (de Souza et al. 2014).

To generate more ethanol per unit area of sugarcane, it is necessary to improve sugarcane varieties to produce higher sucrose and biomass. Development of elite of sugarcane varieties is an extremely arduous task when compared to other crops' breeding, mainly due to its complex genome and hindrance in viable fuzz production. Improvement of sugarcane varieties through biotechnological tools is a feasible option, but it has yielded limited success yet. Targeting bioethanol-related traits through integrated conventional and biotechnological approaches will enhance the viability and suitability of sugarcane for biofuel and bioenergy production.

There is huge unexplored potential in sugarcane regarding its energy parameters, as earlier cane-breeding efforts have only focused on sugar yields. Thus, sugarcane breeding offers greater chances of success for any breeding program prioritizing biomass instead of sugar potential since a plateau is supposed to have been reached regarding sugar parameters (Khan et al. 2017a). Energy cane varieties, recently introduced, are an example of the dramatic improvement of sugarcane for biomass production which can find applications as a source of second-generation ethanol.

1.8 Possibilities of Enhancing the Potential of Sugarcane for Biofuels and Bioenergy Production

Industrial and molecular approaches are anticipated to play substantial role in improving the process efficiencies and making the sugarcane bioenergy production process even promising. Various energy-related traits can be introduced/manipulated in sugarcane crop for the same purpose.

One of the major problems in the production of second-generation bioethanol from plant cell walls, as in sugarcane, is the presence of large amounts of pentoses in cell wall polysaccharides. With advancements in biotechnology and genetic engineering, now it has become possible to identify and discover the candidate genes which may be used successfully for developing structural and architectural changes in the cell wall. Sugarcane's cell wall engineering is one of most promising options to make the second-generation bioethanol production economical, reducing the need of expensive pretreatment steps.

In many studies, modification in cell wall properties has been successfully accomplished and evaluated in the field with encouraging results. Jung et al. (2013) reported that caffeic acid *O*-methyltransferase (*COMT*) can be lowered in transgenic sugarcane plants using RNAi, which resulted in transcript reduction by 80–91%. A total lignin content reduction of 6–12% was observed in different genetically modified sugarcane lines. The lignin reduction improved 19–23% saccharification efficiency with non-significant effect on biomass yield and other useful agronomic characters. It was also recorded that biomass from transgenic sugarcane lines having modified cell wall characteristics required almost one third of the hydrolysis time and three- to fourfold less amount of enzymes to release an equal or greater amount of fermentable sugar than the wild-type plants (Jung et al. 2013).

The enzymes involved in lignin synthesis such as Cinnamyl Alcohol Dehydrogenase (CAD) have also been manipulated to change the cell wall composition. Moreover, transgenic sugarcane lines have been seen to produce higher sucrose and fiber contents in immature internodes by down regulating pyrophosphate (fructose 6-phosphate 1-phosphotransferase) (Groenewald and Botha 2008; van der Merwe et al. 2010).

A reduction in lignocellulosic recalcitrance of biomass to carry out saccharification through modification of lignin biosynthesis is expected to greatly benefit the economic competitiveness of sugarcane as a biofuel feedstock (Jung et al. 2013; Kandel et al. 2018). However, 100% saccharification efficiency has not been achieved till date. Hence, cell wall characteristics render some constraints for the hydrolysis which need to be tackled to make the second-generation cane biofuel more cost-effective and profitable.

Moreover, for success of 2G bioethanol production, along with cell wall modulations, numerous other approaches can also be considered. Regarding industrial conversion, identification and characterization of efficient hydrolytic enzymes may speed up the conversion of sugarcane cell wall polysaccharides into fermentable sugars. The cell wall organization and the complexity of cross-linked domains do not permit cellulases alone to release all of the fermentable sugars present in the sugarcane cell wall. Ultimately, for complete digestion of cell walls, large amounts of enzymes are required. Extra proficient hydrolysis could only be attained by using efficient and improved hydrolases.

In recent past, in-planta enzymes are being targeted to introduce the cane varieties self-producing the enzymes needed for cell wall digestion. Such endogenous hydrolases are supposed to be induced at the crop maturity. In this way, the hydrolytic activity of in-planta activated enzymes will loosen the cell wall, making it vulnerable toward disassembly and release of fermentable sugars in industrial processing. Hence, developments in sugarcane research can play a huge role in its future as a bioenergy source. Through genetic manipulation and industrial improvements, sugarcane will have an even greater role to play as a promising feedstock for bioenergy engenderment.

1.9 Challenges and Future Prospects

To fulfill the increasing demands of fuel and energy, in context of growing population, depleting fossil fuel resources, and climate change mitigation, it is important to explore alternative energy resources. Biological sources can play a paramount role in satisfying the world's energy needs; however, this must not compromise the food production—one of the major arguments against bioenergy crops. Sugarcane, being a huge biomass and sucrose producer, is an excellent bioenergy crop grown in many countries around the world. Nevertheless, using this crop only for energy production through conventional approaches will give rise to food vs. fuel issues; therefore, only wise expansion should be adopted to make the shift feasible and sustainable.

Various routes of extracting fuels and energy can be exploited in case of sugarcane. In order to deal with the sustainability and food security issues, enhancing crop production in a country and diverting only excess sucrose toward ethanol production is one solution, whereas use of only lignocellulosic materials of this huge biomass producer is the other one. Additionally, production of energy cane only on marginal barren lands also provides an answer to the question of sustainability of cane bioenergy production (Khan et al. 2017b). However, to make use of lignocellulosic biomass of sugarcane rather than molasses, pretreatment technologies need to be improved and made cost-effective. In spite of current limitations, with the advances in crop improvement and processing technology, it is anticipated that sugarcane will become an even popular and economical source of energy because of its exceptional characteristics (Yuan et al. 2008).

To date, Brazil is the only country which is utilizing the appropriate potential of sugarcane crop as a biofuel resource. There are many other sugarcane growing countries, where this crop is being solely employed for sugar production and it is not finding applications for the other use(s). Having unique industrial and agronomic advantages over any other crop energy source, sugarcane provides excellent opportunities to harvest its energy potential for meeting the fuel and energy needs of the long list of cane-growing countries.

Hence, in the future, sugarcane produce will be used as feedstock for bioenergy purposes as well in many countries of the world rather than as sugar crop only (de Souza et al. 2014). Nevertheless, apart from agronomic and industrial perspectives, such role of sugarcane would also face policy challenges, as being a multi-stakeholders' industry, adopting any new model in a particular country would need government support through apposite policies. Suitable policies are necessary to facilitate the small-scale cane growers, launch mandatory ethanol blends, and introduce compatible car engines. Proper planning is also needed for developing sustainable cane industry having minimal economic risks and impact on food security and biodiversity.

1.10 Conclusion

Sugarcane is largest agricultural commodity with respect to total production. Its high photosynthetic efficiency, and tillering and ratooning ability make this crop extremely attractive to be used as an energy crop. Sugarcane's excess sucrose can be diverted to bioethanol production through first-generation approaches, while its bagasse, trash, and leaves can all be subjected to second-generation ethanol and bioelectricity production. Very recently, newly developed energy cane varieties are also being exploited for production of second-generation biofuel. Sugarcane has a wide range of adaptability and is being grown in a number of countries. However, its potential as an energy crop has not been explored extensively to date. Adoption of sugarcane as an energy crop can offer huge economic incentives to many of the cane-growing countries around the world and can help the world mitigate GHG emissions to combat climate change.

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Chapter 2
Biofuel Production from Sugarcane: Various Routes of Harvesting Energy from the Crop

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Gisele Silva de Aquino, and Reges Heinrichs**

2.1 Introduction

Global energy supply comes mainly from fossil fuels (oil, natural gas, and coal), which contribute by more than 82% to help the world meet its energy needs (Ho et al. 2014). Fossil fuels are a polluting form of energy source in terms of greenhouse gas (GHG) emissions; 56.6% of all GHG emissions come from burning oil, natural gas, and coal (Intergovernmental Panel on Climate Change [IPCC] 2011). GHG emissions lead to anthropocentric global warming—the main contributor toward climate change (Brazilian Sugarcane Industry Association [UNICA] 2018).

Thus, growing global demand for food, energy, and water is putting pressure on the sustainability of the "planetary boundaries," necessitating actions for sustainable production across all sectors (Rockström et al. 2009). Considering that 60% of the oil use is for transportation sector (Silva 2009), the alternative and renewable fuel production became essential. Bioethanol has become an excellent option for its efficiency, energy balance, and cost, causing several countries to compete in its production and turning the world's attention to this source of energy.

Bioethanol can be produced from several types of feedstocks, which are classified into three categories: (i) sucrose-containing feedstocks, such as sugarcane (*Saccharum* spp.), beets (*Beta vulgaris*), sucrose sorghum (*Sorghum* spp.), and

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fruits; (ii) starch materials such as maize (*Zea mays*), sorghum (*Sorghum* spp.), wheat (*Triticum* spp.), rice (*Oryza sativa*), potato (*Solanum tuberosum*), manioc (*Manihot esculenta*), sweet potato (*Ipomoea batatas*), and barley (*Hordeum vulgare*); and (iii) lignin-cellulose materials, i.e., wood, straw, and grass (Balat 2010; Leite and Leal 2007; Solomon and Bailis 2014). Bioethanol can be developed in a sustainable way and will contribute to promoting the use of renewable sources.

For a certain production line in a mill, comparison of feedstocks includes several factors such as biomass chemical composition, availability and soil usage practices of the area, energetic balance, logistics' costs, as well as the feedstock's direct economic value (Aquino et al. 2018). Through analysis of these factors influencing bioethanol production at mills, it is noted that the feedstock availability is the main determinant since it can vary from season to season and depends largely on geographical location of the corporation (Aquino et al. 2017; Balat 2010; Fageria et al. 2013; Solomon and Bailis 2014).

Sugarcane is not only an excellent source of bioethanol from sucrose fermentation, but it also has huge biomass potential to provide lignocellulosic material for biofuel engenderment (Henrichs et al. 2017). Conversion of lignocellulosic material or biomass in to fermented sugars for bioethanol production is considered a promising alternative to increase the biofuel production in order to attend the global energy demands. Bioethanol obtained from sucrose of the sugarcane (*Saccharum officinarum* L.) is called "first-generation." Whereas, the production of lignocellulosic bioethanol from the plant cell wall is defined as "second-generation." Moreover, studies to obtain third- and fourth-generation bioethanol from other sources are also underway (Buckeridge et al. 2010; Carvalho et al. 2013).

Lignocellulosic biomass is considered as the future feedstock for bioethanol production because of its socioeconomic benefits and huge availability (Cardona et al. 2010). Apart from sugarcane, lignocellulosic biomass can be collected from various sources which include (i) harvest residues (corn straw), (ii) hardwood (alpine poplar, *Populus tremula*), (iii) conifer wood (pine tree, *Pinus* spp.), (iv) cellulose residues (recycled paper sludge, newspapers, etc.), (v) herbaceous biomass (alfalfa, *Medicago sativa*, reed stick (*Phalaris arundinacea*), etc.), and (vi) municipal solid residues (Cardona et al. 2010; Chemmés et al. 2013).

Bagasse and sugarcane straw have been the most widely used feedstocks for second-generation (2G) bioethanol. Bagasse is a leftover lignin-cellulose residue obtained after the sugarcane milling process that produces the cane broth. Sugar and bioethanol production generate huge amounts of bagasse as by-product, which then is employed for energy generation for the boilers and for the national grid. Brazil alone milled more than 635 million tons of sugarcane in the 2017/2018, generating up to 285 million tons of residues as bagasse and straw (Companhia Nacional de Abastecimento [CONAB] 2018). Around 66.6% of the total energy that can be produced by sugarcane is available as residues. These substrates can be used for cogeneration or to yield bioethanol and other products. Silva (2009) analyzed the energy contained in basic sugarcane composition and compared it against gasoline, reporting that sugarcane has great potential in terms of its energy contents (Fig. 2.1).

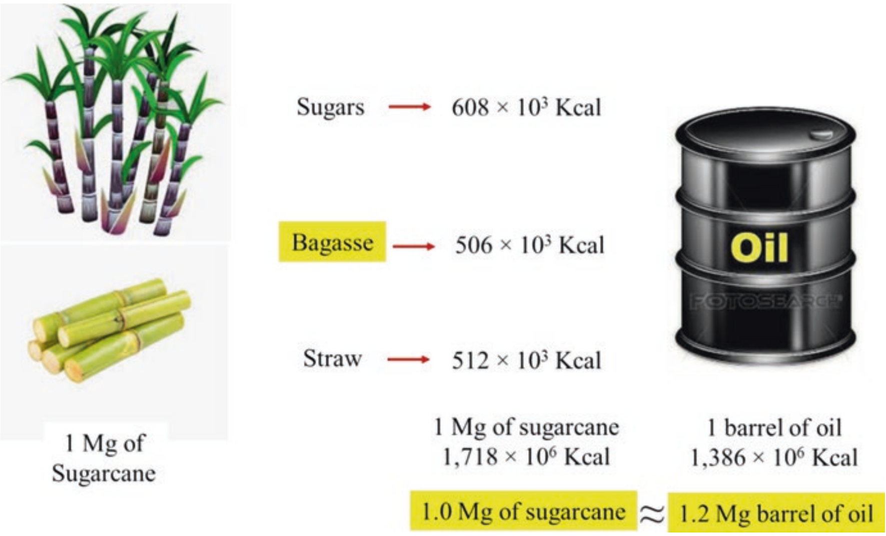

Fig. 2.1 Comparison of energy contents of sugarcane against gasoline. (Adapted from Silva 2009)

2.2 Sucrose for Bioethanol Production (First-Generation Cane Biofuels)

In order to reduce the dependence on fossil fuels and to mitigate the climate change, many countries are adopting mandatory blends of biofuels, expanding the prospects for consolidation of a global market for renewable energy sources. At the beginning of 2014, the number of countries using mandates for biofuel blending was estimated to be around 35 (Dias et al. 2015; UNICA 2018). With an increasing number of countries adopting biofuels, world is anticipated to benefit from the consequent stability in fuel bioethanol and gasoline prices, as well as environmental benefits due to reduction of greenhouse gas emissions (GGE). Moreover, such efforts are also expected to contribute toward energy security of many of the countries. These factors have already resulted in significant adoption of biofuels in Americas. Moreover, European Union's program called Directive on Renewable Energy (DRE) has also proposed that 10% of all energy consumed in the 28 countries should be from clean sources by 2020 (Dias et al. 2015; UNICA 2018).

In South America, with addition of 25% bioethanol to gasoline, Brazil is in vanguard in terms of relative consumption, being the country with the largest substitution of gasoline for bioethanol in the world. Paraguay ranks next, with 24% mixing. Chile and Argentina, more modest, add 5% of biofuel to their fossil fuel. In sum, 13 Latin countries already use or are in an advanced process to establish the biofuel blends—as is the case of Uruguay. With nine provinces using the 10% bioethanol blend, China leads the mandates on Asian continent. China also aims to increase the blend to 15% by 2020. Philippines is targeting 10%, while India and Vietnam aim mixing 5% (Table 2.1) (UNICA 2018).

Table 2.1 Blends of bioethanol to gasoline in some countries of the world

America	Africa	Asia and Oceania
Argentina—5% bioethanol	Angola—10% bioethanol	China—10% bioethanol
Brazil—25% bioethanol	Ethiopia—5% bioethanol	India—5% bioethanol
Canada—5% bioethanol	Kenya—10% bioethanol	Indonesia—3% bioethanol
Chile—5% bioethanol	Malawi—10% bioethanol	South Korea—2% bioethanol
Costa Rica—7% bioethanol	Sudan—5% bioethanol	Philippines—10% bioethanol
Ecuador—5% bioethanol		Thailand—5% bioethanol
USA—10% bioethanol		Vietnam—5% bioethanol
Mexico—2% bioethanol		

Source: UNICA (2018) and Dias et al. (2015)

The first-generation (1G) bioethanol can be generated from various feedstocks such as sugarcane, sorghum, sugar beet, corn (*Zea mays*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), manioc (*Manihot esculenta*), and candy (*Ipomoea batatas*). It is evident that for producing first-generation bioethanol, easily withdrawable sugar or starch sources are used. Sugarcane has certain advantages in this context; its juice already contains approximately 20% sucrose, and it does not need pretreatment step for bioethanol production, while corn, the other competitor in this reference, needs to first pass through a hydrolysis step so that sugar can be produced, which is then subjected to fermentation (Lima and Natalense 2010).

Sugarcane and corn are the two major crops used for first-generation bioethanol production, accounting for more than 80% of the total bioethanol biofuels in the world. However, large adoption of first-generation biofuels from grains is considered debatable because of the perception that such crops compete with food production and can have negative impact on food prices. Moreover, land requirements of these crops, e.g., corn, also present challenging situation. The average bioethanol production capacity of sugarcane is 7500–8000 L ha^{-1}, while that of corn is 3460–4020 L ha^{-1} (Mussatto et al. 2010). Hence, for yielding same amount of bioethanol, corn requires two times higher land than the sugarcane.

One ton of sugarcane contains about 1718×10^6 Kcal energy, roughly equal to energy contained in 1.2 barrels of oil as one barrel of oil has 1386×10^6 Kcal energy (see Fig. 2.1). In sugarcane, one-third of the energy is contained in juice, another one-third in bagasse, and the remaining one-third portion in sugarcane straw (Souza 2014). Considering the example of Brazil, its 2017/2018 crop harvested 633 million tons of sugarcane, which would have been equivalent to 759 million barrels of oil per year or 2.1 million barrels of oil per day. Out of this huge amount of energy, currently only one-third is well used (Souza 2014).

After harvest, sugarcane is prepared for extraction going through a series of choppers and shredders. Extraction of sugars can be done in mills or diffusers. Employment of mills for this purpose is the most traditional method. However, replacement by diffusing units for sugar extraction is already being realized in units. Extraction by diffusion, among other advantages, decreases the consumption of power and yields lower level of solids in the broth, which facilitates the subsequent physical treatment steps (Rein 2007).

The extracted broth has soluble impurities and solid particles in suspension, which should be removed for sugar and bioethanol production having up to the mark market quality. Removal of impurities for bioethanol production is also important since they can decrease the yield from the fermentation step due to their possible inhibiting action. These contaminants can even make yeast recycling and recovery intricate, because of the presence of solids in suspension. This step is generally called broth physical treatment, in which solids composed by bagasse are removed in cyclones and filters. The broth containing soluble impurities is sent to the next stage of chemical treatment (Santos et al. 2012a).

2.2.1 Production Process

Following are the main steps involved in 1G bioethanol production from sugarcane.

2.2.1.1 Broth Chemical Treatment

During the production process, the broth goes through coagulation to remove impurities. In order to achieve that, chemical components such as calcium oxide (CaO) and phosphoric acid (H_3PO_3) are used. This is an important step for sugar production, in which the broth is neutralized by correcting pH values from ~5.0 to approximately 7.0; neutralization prevents sucrose degradation which can suffer inversion in acidic pH (Rein 2007). During manufacturing, oxide calcium (CaO) reacts with phosphoric acid (H_3PO_3), forming a solid material that coagulates impurities (Rein 2007). Polymeric coagulators are employed in small amounts to help with this process. The solution is left for decantation in a tank, after which the clarified broth is sent to the concentration step.

The formed sludge is sent to filters, with the bagasse fine fraction that passes through the broth being recovered during the liquid extraction and sent to the beginning of this step, in which the solid fraction is disposed (Rein 2007). This step is distinct for sugar and bioethanol production. For yielding sugar, besides the mentioned reagent, the broth goes through a sulfitation step in order to eliminate impurities that confer color to the product (Hamerski 2009).

2.2.1.2 Concentration Step for Sugar and Bioethanol Production

The clarified broth has a concentration of approximately 15° brix for sugar yield. It must pass through a concentration operation to reach approximately 60° brix. In general, concentration is done in five to six effect evaporators in which a pressure above atmospheric is avoided to obtain the sugarcane broth concentration (Dias 2008), as such conditions can cause higher loss of sugars and final sugar quality (Aguilar et al. 1989; Rein 2007).

The clarified broth sent for bioethanol production must have a concentration between 19° and 22° brix (Copersucar 2018) for an adequate fermentation production. In order to accomplish this, molasses resulting from sugar production is mixed to the broth. Water is added to the solution when the final mix concentration is higher than the optimum range for fermentation.

2.2.1.3 Fermentation

The fermentation step represents the main part during the biofuel production process, in which sugars from the broth are converted into bioethanol and other derived products. Alcoholic fermentation is a biochemical process, in which the substrate is metabolized under yeast enzymatic action by metabolic pathways. Normally, bioethanol production is done industrially by *Saccharomyces cerevisiae* yeast. This microorganism is of a facultative aerobic type, meaning that sugars present under an oxygen-filled process are transformed into sterols and unsaturated carboxylic acids, essential to cellular membrane synthesis (Munroe 1994), CO_2, and H_2O. Under the absence of oxygen (O_2), this microorganism performs an anaerobic process, with most sugars being metabolized to bioethanol and CO_2. A simplified reaction for the alcoholic fermentation process is presented in the following equation:

$$C_6H_{12}O_6 \Leftrightarrow 2C_2H_5OH + 2CO_2$$

Twelve different reactions are part of this pathway of bioethanol production. An enzyme catalyzes each reaction (Lima et al. 2001). Main fermentation steps are sucrose hydrolysis, which produce glucose and fructose, followed by the glucose and fructose transformation into bioethanol. This reaction is exothermic; therefore, the temperature of the reaction medium must be maintained between 26 and 35 °C to obtain good yield from the industrial production process, according to the type of process employed. Other coproducts such as glycerol and acetic acid are also produced in smaller amounts during bioethanol production (Santos et al. 2012a). Figure 2.2 presents main routes for bioethanol and sugar production as well as residues yields, such as vinasse, for a better understanding of the first-generation bioethanol production process (Bernardo Neto 2009).

Considering the high number of reactions catalyzed by enzymes during the fermentation process, bioethanol production, as well as the rate of cell reproduction and substrate consumption, is strongly influenced by various other variables such as pressure, temperature, pH, and the concentration of reagents and products. Furthermore, contamination of the medium by other microorganisms can decrease or even prevent bioethanol production by yeasts (Steckelberg 2001). There are also other types of yeasts and bacteria capable of conducting alcoholic fermentation by

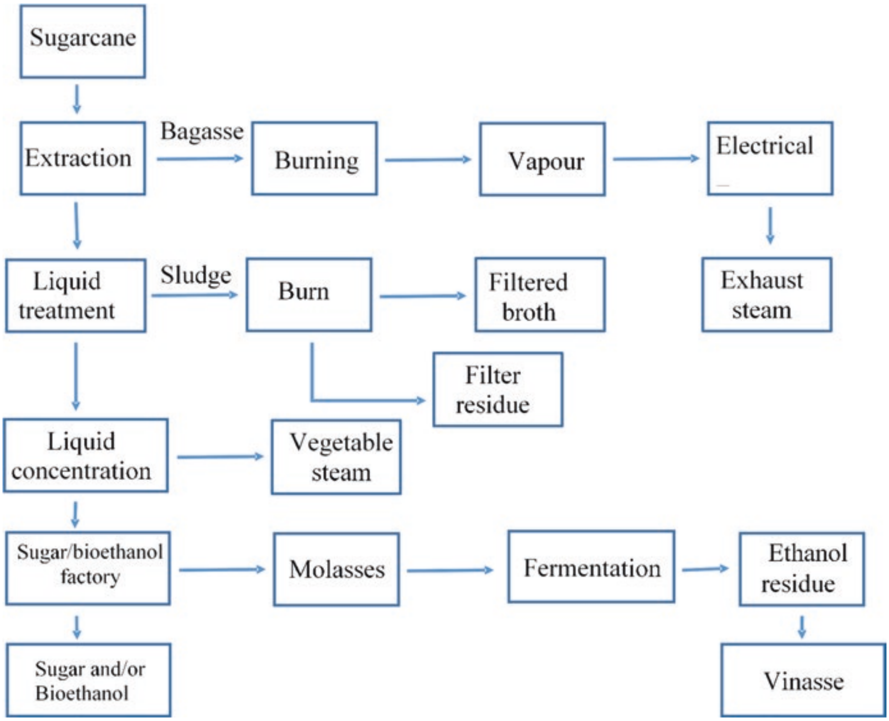

Fig. 2.2 Main steps and processes for bioethanol (first-generation) and sugar production from sugarcane. (Adapted from Silva 2009)

metabolizing the sugar into CO_2 and bioethanol (Oliveira and Mantovani 2009). However, use of *Saccharomyces cerevisiae* for industrial processes is the popular option, due to ability of the said species to support highly drastic conditions in this non-sterile process (Steckelberg 2001).

There are three types of fermentation processes used to obtain bioethanol at an industrial scale: (i) simple batch process, (ii) feeded batch process (Melle-Boinot process), and (iii) continuous process. In simple batch process, the reactor is loaded with mold and yeast in the simple batch production, with the fermentation process occurring until the yeast activity ceases by lack of nutrient or by an excess of formed bioethanol. This process configuration is slow and requires the reactor to be cleaned at each batch and loaded with mold and yeast again. Employment of the simple batch process was vastly used until the feeded batch process was developed (Zarpellon and Andrietta 1992). The fed batch process was generalized in the late 1960s and the 1970s. The feeded batch process is defined as a technique in microbial processes where one or more nutrients are added to the fermenter during cultivation and the products generated remain until the end of fermentation (Guidini 2013).

2.3 Biomass for Cane Biofuels (Second-Generation Bioethanol)

2.3.1 *Biomass Composition of Sugarcane*

Chemical composition of lignocellulosic materials, which is greatly affected by the genetic and environmental factors, is crucial factor in second-generation biofuel production (Balat 2010; Gómez et al. 2014; Hamelinck et al. 2005). Lignocellulosic materials are polymers of carbohydrate complexes, basically, of three components: cellulose $(C_6H_{10}O_5)_x$, hemicellulose $(C_5H_8O_4)_m$, and lignin $[C_9H_{10}O_3(OCH_3)]_n$ (see Fig. 2.3). Such components represent approximately 90% of the dry weight of cane, whereas 10% of the remaining mass is contributed by extractives and ashes (Balat 2010).

Cellulose is a linear polysaccharide having a crystalline linear structure. It is a homopolymer of repeated glucose units connected by β-1, 4 glycosidic bonds (Ogeda and Petri 2010; Sarkar et al. 2012). Cellulose chains are packed into microfibriles, which are stabilized through hydrogen bonds (Brodeur et al. 2011; Hendriks and Zeeman 2009). Hemicellulose is a much-ramified short heteropolymer formed mainly by pentose (D-xylose and L-arabinose), hexoses (D-glucose, D-mannose,

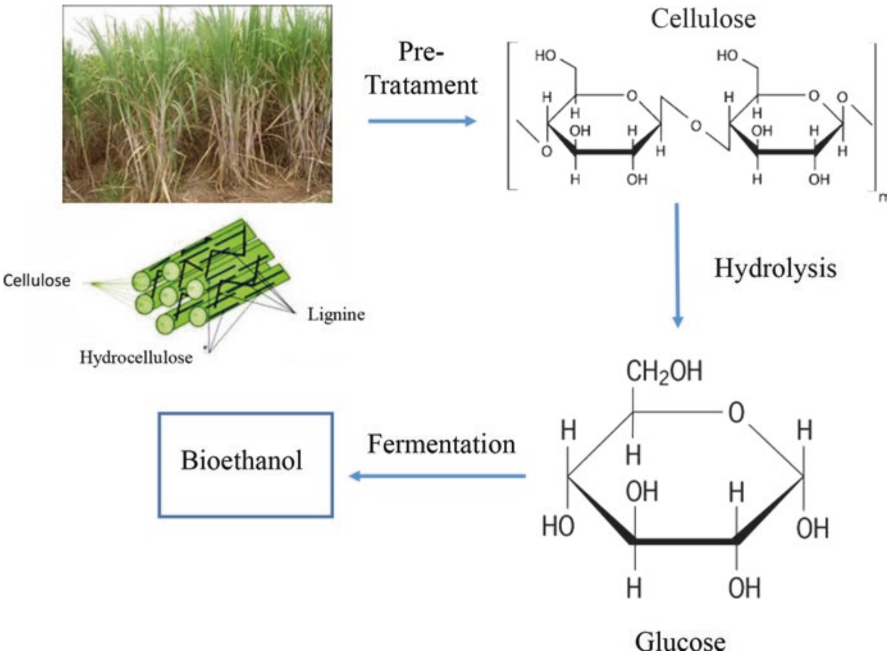

Fig. 2.3 Schematic representation of bioethanol from lignocellulosic biomass (second-generation biofuel). (Adapted from Santos et al. 2012a)

D-galactose), glucuronic acid, and mannuronic acid (Brodeur et al. 2011; Ogeda and Petri 2010; Sarkar et al. 2012).

Solubility of different hemicellulose components, in a decreasing order, is as follows: mannose > xylose > glucose > arabinose > galactose (Saha 2003). Their solubilization increases with an increase of temperature and depends on other factors such as component humidity and pH as well (Hendriks and Zeeman 2009). Lignin is an amorphous compound formed by tridimensional networks composed by interconnected phenylpropane units. These components, together, characterize the rigidity of the plant cell wall, its oxidative tension, and resistance against a microbial attack, due to its hydrophobic nature (Brodeur et al. 2011; Hendriks and Zeeman 2009; Ogeda and Petri 2010; Sarkar et al. 2012).

2.3.2 Sugarcane Biomass for Biofuels

The search for bioethanol extracted from cellulose is inspiring an increasing number of researchers worldwide, motivated by the aim to increase productivity in the sugarcane bioenergetics sector without competing with food production (Marques 2009). Projections indicate that this approach could produce approximately 300 liters of bioethanol per ton of dried bagasse, increasing the per hectare bioethanol yield by up to 100% (Araújo et al. 2013). Some authors have reported that one ton of sugarcane straw produces 287 L of second-generation bioethanol and 80 L of first-generation ethanol (Santos et al. 2012b). Besides this, cellulosic bioethanol presents a high growth and expansion potential as it is produced from residues and does not compete with the food/sucrose production (Marques 2009).

Bioethanol production from sugarcane in Brazil (the largest cane biofuel producer) is currently done through traditional manner, using alcoholic fermentation of the broth sucrose and its distillation. Meanwhile, three large-scale second-generation bioethanol plants with a total capacity of 127 million liters per year are already in operation in Brazil. According to Hamelinck et al. (2005), sugarcane cellulosic bioethanol is produced from wall cell polysaccharides of the sugarcane (see Fig. 2.3) (Costa and Bocchi 2012).

According to Cardona et al. (2010) and Araújo et al. (2013), the objective in the sugarcane sector is to employ sugarcane bagasse and straw, sources of cellulose which in fact contain approx. Two-third of the total sugarcane energy. Thus, subjecting cane residues to hydrolysis and transforming them into biofuels is of great interest (see Fig. 2.3).

The bioethanol obtained from bagasse and sugarcane straw can be produced in the same place as conventional bioethanol (1G). The possibility of integration of the industrial process for cellulosic bioethanol gives the option to restructure the existing plants or the integration of new facilities close to the existing ones. In general, integration can be carried out at different levels namely, sharing of equipment, energy integration (sharing of thermal exchange currents and utilities), reuse of materials, recycling of chains, and integrated effluent treatments (Lima and Natalense 2010).

Second-generation bioethanol yield starts with sugarcane reception at the mill plant and separation into different types of fibers (stem and cane straw). The materials are then shredded and processed separately by hydrolysis (Oliveira et al. 2013; Silva 2009). Sugarcane straw is composed of all the aerial portion of plant, except industrializable stems. It is composed of cellulose, hemicellulose, and lignin, in approximate proportions of 40, 30, and 25%, respectively. Studies conducted by Silva (2009) with *in natura* sugarcane straw showed that this material presents 38% cellulose, 29% hemicellulose, and 24% lignin. Silva et al. (2007) verified that the straw presents an ash content between two and four times higher than bagasse, depending upon the factors like location, weather conditions, stage of plant development, and the sugarcane cultivar (Santos et al. 2012a). In Table 2.2 are some components that can be used for production of bioethanol, sugar, and derivatives.

Major step toward yielding second-generation bioethanol is the degradation of cell wall to use polysaccharides as a source of fermentable sugars (Silva 2014). However, cell wall's structure is complex and hard; moreover, the disaggregation process must preserve the monosaccharides which will be used for fermentation (Piacente et al. 2015). Hydrolysis of the cellulose into glucose catalyzed by cellulase enzymes is extremely slow, and has low yield, mainly due to the highly crystalized structure of cellulose, which makes the substrate access to the active sites very difficult. This impairment increases over time as cellulase physically adsorbs over lignin. Besides this, lignin also hides the cellulosic surface restricting hydrolysis and hindering the fiber swelling (Chemmés et al. 2013; Santos et al. 2012a).

Therefore, a pretreatment step is essential to break the lignin-cellulose crystalline structure to remove lignin, exposing cellulose and hemicellulose molecules to enzymatic action. Normally, enzymatic hydrolysis has a sugar yield lesser than 20%. However, if a pretreatment step is employed, yield can be augmented to 90%. Physical pretreatment is based on reducing the particle size through milling, and augmenting enzymatic performance through an increase in surface area, and in some cases by reduction of polymerization degree and cellulose crystallinity (Santos et al. 2012a). A dilute acid solution is used for the purpose followed by heating at 140–200 °C. However, the parameters of these steps need to be carefully optimized as if the degradation is very intense, furfural compounds are formed which are toxic to the yeast that is to be used in the fermentation stage. Hence, when hydrolyzing a mixture of cellulose and hemicellulose, the temporal disconnection of breaks of

Table 2.2 Sugarcane plant components that can be used for production of bioethanol, sugar, and derivatives

Components	Amount
Stem production (ton ha^{-1} year^{-1})	70.0
Fiber (%)	14.0
Straw (%)	14.0
Pol (%)	14.5
Total of fibers (ton ha^{-1} year^{-1})	19.3
Primary energy (GJ ha^{-1} year^{-1})	520.0
Residue after cane processing (ton ha^{-1} year^{-1})	23.3

Adapted from Bernardo Neto (2009)

glycosidic bonds of each type of polysaccharide is a challenge in fermentable monosaccharaides production (Chemmés et al. 2013).

In summary, obtaining bioethanol from biomass involves two steps. The first one involves polysaccharides' hydrolysis generating mono- and disaccharides, whereas the second step encompasses fermentation of mono- and disaccharides into bioethanol. Cellulose hydrolysis generates glucose and cellobiose, while lignin and hemicellulose hydrolysis generate sugars and subproducts (mainly diphenols, phenylpropane derivatives, ketones, furfural, and acetic acid), which can often inhibit microbial fermentation as depicted in Fig. 2.4 (Pietrobon 2008).

Studies point out that while producing one million liters of bioethanol from sugarcane broth through first-generation technology, an additional production of 150 thousand liters of bioethanol from bagasse can be realized using hydrolysis technology (Marques 2009; Santos et al. 2012a). It is estimated that by 2025, with perfected techniques, the same production could have an increase of 400 thousand liters from the recovered bagasse (Marques 2009). Since straw is produced in large amounts in sugarcane fields, it is also an excellent source of cellulose for the industry for second-generation processing (Aquino et al. 2017; Rocha et al. 2012).

2.3.3 Employment of Bagasse for Other Means

Besides being a source of bioethanol, bagasse of sugarcane production also has many other applications, such as forage, animal feed, especially for ruminants (Siqueira et al. 2012), and cogeneration of electrical energy (Dantas 2010).

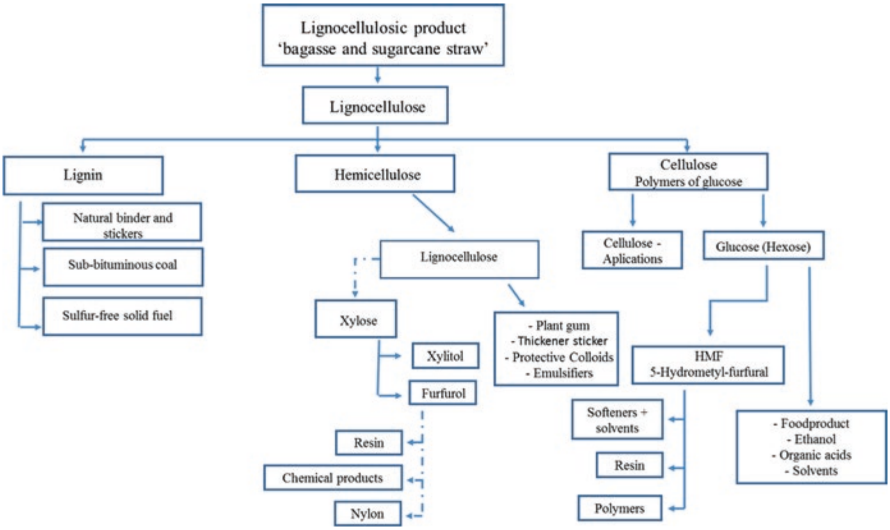

Fig. 2.4 Schematic diagram for bioethanol and other derivatives' production through second-generation process. (Adapted from Bernardo Neto 2009)

Hydrolysis of 38.4 tons of bagasse of sugarcane will allow production of 12.4 tons of fermentable sugars, which can be converted into 7086 liters of bioethanol. Additionally, it will also yield 3.9 tons of lignin, which can cogenerate 2.4 MWh of electricity. Moreover, using the straw from same sugarcane can generate 4.9 MWh of energy. The balance is 6.0 tons of sucrose, 10.5 thousand liters of bioethanol, and 7.3 MWh of electricity, which shows an increase in bioethanol production by more than 200% as a direct reflex of employment of hydrolysis technology (Matsuoka et al. 2012).

Considering the case of Brazil, the largest cane bioethanol producer, Silva et al. (2007) and UNICA (2018) mentioned that sugarcane bagasse is being produced in higher amounts in recent years due to sugarcane industrialization and an increase in the cane-planted area. In addition, an improvement of energy balance of old mills and higher activity of autonomous distilleries has amplified the percentage of left-overs, considerably. It is estimated that 5–12 million tons of this material is produced per year, corresponding to approximately 30% of the total milled sugarcane, that can be used for 2G fuel production (Costa and Bocchi 2012; Silva et al. 2007).

Apart from finding applications in fuel and energy sector, bagasse can be employed in other industries as well. Novel products have been launched in the market in this regard, such as fibrocement—a cement in which bagasse is used for reinforcing and improving its resistance (Costa and Bocchi 2012). Moreover, bagasse fibers can be employed in cosmetics, already being produced in a large scale, soaps in exfoliating bars and hydrating lotion (see Fig. 2.4). Even more, bagasse is used for feeding livestock as well (Torres and Costa 2004).

2.4 Sugarcane for Bioelectricity Production

The population growth, especially of developing countries, demands more food and energy, and meeting these has become a challenge for production and consumption centers (Trombeta and Caixeta Filho 2017). From 1965 until 2010, the world population increased from 3.29 to 6.92 billion and is estimated to grow further by 21.6% reaching 8.42 billion people before 2030 (FAOSTAT 2015). Consequently, population growth requires high amount of energy in next decades to meet our basic human needs (Aquino et al. 2018).

Global energy supply comes mainly from fossil fuels (oil, natural gas, and coal), which contribute by more than 82% to help the world meet its energy needs (Ho et al. 2014). Fossil fuels are a polluting form of energy source in terms of greenhouse gas (GHG) emissions as 56.6% of all GHG emissions come from burning oil, natural gas, and coal (IPCC 2011). Thus, the goal of minimizing greenhouse gas emissions is an important paradigm related to mitigation of environmental impacts of fuels, reinforcing the need to use alternative, clean, and renewable sources of energy (Trombeta and Caixeta Filho 2017).

The sugarcane-energy sector has been highlighted as not only a supplier of feedstock with the highest energy balance for bioethanol production, but it has also been recognized as a mean of fulfilling the electricity needs. The secondary products of sugarcane milling, discarded earlier, have now become a potential feedstock for cogeneration of electric energy, also called bioelectricity. Bioelectricity is a renewable and clean energy made from biomass: like sugarcane residues (bagasse and straw) and other biomass sources (Trombeta and Caixeta Filho 2017).

Sugarcane mills use bagasse as feedstock in steam systems that operate efficiently to generate electricity. In Brazil, the bioelectricity produced from sugarcane bagasse and supplied to the national grid reached 21.444 GWh (Gigawatt-hour) in 2017. The energy supplied to the grid was enough to fulfill the electricity needs of 11.4 million residences over a year, apart from ceasing the emission of 8.1 million tons of CO_2 (Anuário Brasileiro de Cana-de-Açúcar 2018). Compared to fossil fuels, bioelectricity from sugarcane is an extremely sustainable alternative. Appropriate utilization of all sugarcane residues can yield highest energy balance in comparison to other options in this regard, and that too, without competing food production if second-generation routes are employed. However, the product is under-utilized; the full exploitation of biomass produced by sugarcane in 2017/2018 growing season is supposed to increase the bioelectricity production to 144.8 TWh (Terawatt-hour). The use of the straw would generate 78.2 TWh; bagasse 46.0 TWh; and biogas 20.5 TWh. Exports to the electrical grid in 2017 amounted to 21.4 TWh, up 1% from the previous year. Even this also represented just 15% of the estimated technical potential for the 2017/2018 cropping season (Anuário Brasileiro de Cana-de-Açúcar 2018).

2.5 Sugarcane Straw for Energy Production

Due to availability of new and more advanced agricultural and industrial technologies, it has become possible to recover the industrial benefits from all of the agricultural residues of sugarcane, and more recently, the use of straw has gained importance in this regard. Straw is composed of 54% dry leaves and 46% tops (Franco et al. 2013), whereas moisture content at harvest is around 30–60% (Michelazzo and Braunbeck 2008). At harvesting, tops have moisture ranging from 60% to 70%, while dry leaves have moisture content of around ~10% (Franco et al. 2013).

Sugarcane straw contains about 19.0–34.4% lignin, 29–44% cellulose, and 27–31% hemicelluloses, in addition to 2.4–7.9% ash as lignocellulosic part (Table 2.2) (Szczerbowski et al. 2014). Sugarcane straw presents nitrogen (N), phosphorus (P), and potassium (K) nutrient concentrations ranging from 4.4 to 5.4, 0.1 to 0.7, and 2.8 to 10.8 g kg^{-1}, respectively (Andreotti et al. 2015; Fortes et al. 2013). In relation to the calorific value of sugarcane residue produced, each ton of straw collected for generation of energy is equivalent to 1.7–1.8 tons of bagasse produced at the mill (Aquino et al. 2018).

Straw can be fed to the boilers along with the bagasse, and this amalgam can produce three different forms of energy, i.e., (i) thermal energy that is used for heating in the sugar and bioethanol production process; (ii) mechanical energy which drives the machinery and equipment for extraction and preparation of the broth, in addition to running turbines for energy engenderment, thus transforming it into electric energy; and (iii) electric energy used for mill's own consumption or supply to the grid.

Although straw is an effective feedstock, there are challenges associated with industrial applications of this material for energy production as its indiscriminate removal from the field cannot only affect sugarcane productivity but also the sustainability of production system. Straw mulch over the soil surface brings certain chemical, physical, and biological changes in the agricultural environment, such as increase in soil organic matter, decrease in thermal fluctuations of soil's superficial layers, increase in water permeation with low evaporation, erosion control, enhancement of macro- and microfauna, and changes in weed flora (Christoffoleti et al. 2007; Tavares et al. 2010). These parameters and factors directly impact the development, productivity, industrial quality, and longevity of sugarcane (Souza et al. 2005).

Long-term studies were conducted to evaluate the productivity and industrial quality of sugarcane after removing different amounts of straw mulch from the field (Aquino et al. 2015, 2018). In general, it was observed that most of the agronomic benefits could be maintained by ensuring the field quantities of 7–10 tons per hectare of straw, whereas the surplus may be collected from the field for production of second-generation bioethanol or bioelectricity, without any damage to the crop. Hence, sugarcane straw can serve as another source of energy engenderment from cane crop.

2.6 Challenges and Constraints

It is evident that sugarcane biofuels and electricity have a great role to play in world's future energy matrix. However, for achieving full potential of cane as an energy source, it is necessary to optimize and improve current energy generation processes and practices, which are expected to offer more possibilities of gains and cost reduction. Substantial progress has been made for bioethanol production from lignocellulosic materials; however, the transition to mature industrial technology requires additional research and development efforts to address the challenging issues such as better pretreatment technologies, low-cost enzymes, and efficient fermenting strains of microbes. Hence, developments in metabolic and industrial processes can help increase the cost-effectiveness and profitability of cane energy production. Bioelectricity is already considered as another important product of sugar mills. Surplus electric energy production can contribute significantly toward cost reduction of milling operations besides diversification of national energy matrix. However, constraints for expansion of electricity and fuel generation from sugarcane biomass are not only technological but regulatory and political as well because support from the government policies is also a prerequisite before moving toward exploring the full potential and possibilities of energy production from sugarcane.

2.7 Conclusion

Sugarcane has potential to serve as an excellent energy crop. Increasing energy needs of the globe, and the environmental impacts of fossil fuels, have given the bioethanol a status of well-desired and viable substitute. Many routes of cane fuel production such as sucrose fermentation, bagasse utilization, and straw exploitation can be employed for first- and second-generation biofuel production. Moreover, sugarcane can also serve as a source of bioelectricity. Being an extremely efficient energy crop, it provides high-energy balance values. Adoption of cane-derived energy can significantly help in lessening the emission of greenhouse gases and reducing the carbon footprint. With the improvement of technological aspects of energy production processes as well as biological aspects of the cane crop, sugarcane-derived energy is not only expected to become more profitable and cost-effective, but it is also anticipated to play significant role in world's energy matrix.

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Chapter 3
Energy Cane: A Sound Alternative of a Bioenergy Crop for Tropics and Subtropics

Sizuo Matsuoka and Luis Claudio Silva Rubio

Abbreviations

1G	First-generation
2G	Second-generation
ACIAR	Australian Centre for International Agricultural Research
BC_1	First backcross
BC_2	Second backcross
BC_3	Third backcross
COP21	2015 Paris Climate Conference
CSC	Conventional sugarcane
EC	Energy cane
EU	European Union
F_1	First cross hybrid
FAO	Food and Agricultural Organization
GHG	Greenhouse gases
Mha	Million hectares
OECD	Organization for Economic Co-operation and Development
REN21	Renewable Energy Policy Network for the 21st Century
SCOPE/72	Scientific Committee on Problems of the Environment
$t\ ha^{-1}$	tons per hectare
UNFCC	United Nations Framework Convention on Climate Change
USA	United States of America
USDA	United States Department of Agriculture

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3.1 Introduction

According to the paleontologist Wrangham (2009), the discovery of fire was a landmark on human's evolution. He advocates that the possibility of preparing and eating cooked foods made us the way we are today physically, physiologically, psychologically, and sociologically. He meant burning biomass had been a fundamental drive in the forging of the human civilization throughout the last two million years of evolution. Then it came the modern times, and in the past 100 years, humanity experienced the biggest transformation ever by the usage of bioenergy accumulated for millions of years in a concentrated form—the fossil fuels. According to Lovins (2011), the total worldwide energy use grew by 80–90-fold in most revolutionary process in human history since domestication of plants and animals. Now, however, due to its intensive use and abuse, humanity is facing a serious challenge in terms of changing the matrix of energy to counteract the deleterious effect of fossil fuel consumption, mainly to the Earth atmosphere via accumulation of greenhouse gases (GHG). As a result, the issue of development and extensive use of clean energy forms, together with changing attitudes in the use of energy, is considered of urgent need (Lovins 2011).

Several forms of clean energy have been studied, proposed, or put in use as contributors to a cleaner and more sustainable planet. However, many of them require high technology and, consequently, they are not affordable to developing nations. The old biomass energy (bioenergy) has been arguably considered a viable option, but modernly added with more valuable end uses, according to what each nation can afford (Goldemberg 2011; Haberl et al. 2011; Long et al. 2015; Perlack et al. 2005; REN21 2017; Vanholme et al. 2013; Vermerris 2008). This chapter will present and discuss a promising option of dedicated biomass crop, the energy cane (EC) which is particularly suited to tropical and subtropical regions. Before that, however, it is important to introduce and discuss one important concept, the resilience, how it affects crop production and breeding, particularly concerning EC.

3.2 Breeding for Resilience

An agroecosystem is purposely managed to give the plant the best growing condition. However, notwithstanding the best intended farming, the norm is that optimal conditions rarely occur in the field, if any, for an extended time during the season(s) or even during a single day (Blum 2013). The result is the sugarcane crop experiencing the effect of several stressors (Larcher 2003) during its year-round life cycle, even in a week or day basis, therefore needing to withstand such stresses to give a satisfactory yield at harvest (Inman-Bamber and Smith 2005; Monteiro and Sentelhas 2017; Moore 1987). Any stress results in a physiological cost to the plant (Lambers et al. 2008; Rodolfo 2017) and, as result, a negative effect on yield. The level of resilience of a specific cultivar ultimately determines the gap between the attainable and the actual yield (Matsuoka 2017; Monteiro and Sentelhas 2017; Van Ittersum et al. 2013).

The aim of the plant breeding is to produce cultivars that can perform as per the farmers' need. To that end, besides all the characteristics brought by a cultivar, the adaptability and stability are two essential attributes (Eberhart and Russell 1966; Finlay and Wilkinson 1963; Mariotti 1974; Annicchiarico 2002), which are usually evaluated in the final stage of the breeding program, or even after the release of the cultivar (Annicchiarico 2002; Brown and Glaz 2001; Mariotti 1987). The objective is the cultivar thriving well in the specific conditions it will grow, i.e., have good adaptability and enough stability without unexpected underperformance in time and space. A term that can embrace both characteristics together is resilience. Thus, resilience of a cultivar is its capacity to cope with all the several stressors challenging during all its life cycle to allow the prospected yield at the end (Matsuoka 2016, 2017). Darnhofer (2014) and Lengnick (2015), among others, have discussed the importance of resilience in agriculture.

An agroecological environment is extremely complex, being the result of interaction among a suite of factors, both natural and anthropogenic (Coleman 2016; De Deyn and van der Putten 2005; Loomis and Connor 2003; van der Heijden et al. 2008). Although all the efforts are put by the breeders to select plants with the best potential performance, i.e., with the best adaptability and stability, the environment is never in an optimum level, neither in space nor in time. This means that stressors are challenging the resilience of the cultivars all the time and in every patch of land, thus constraining yield (Hall 2014; Hodge 2006; Nelson and Ham 2000; Voroney 2007). The knit of genetics and management practices have been exploited well to increase the productivity of the crops in the last century (Borlaug 2003; Cumo 2016; Fischer et al. 2014; Kingsbury 2009). However, notwithstanding this progress, the average yield of the crops all over the world is well below the attainable productivity. The gap is in the order of 30–50%, some worst cases with 60–70% of reduction (Fischer et al. 2014; Lobell et al. 2009; Monteiro and Sentelhas 2017; van Ittersum et al. 2013). This underperformance of the crops shows that despite all the breeders' efforts and subsequently the farmers giving the best managerial conditions to the crop, they are falling (Evans and Fischer 1999; Jones and Singels 2015; Loomis and Connor 2003; Mueller et al. 2012; van Ittersum et al. 2013). The higher the resilience, i.e., the ability to cope with all the stressors and recovering nearly normal growth, the minor the yield losses will be. In this regard, Denison (2012) arguments that in nature the plants evolved for millions of years to prevail over every acting stressor by natural hybridization and selection, so that breeders should keenly imitate it reproducing the path they've used, taking advantage of the wealth of available gene pool (Dempewolf et al. 2017; Warschefsky et al. 2014).

3.3 Resilience in Sugarcane Breeding

The breeding of plants progressed significantly during last century, the hybridization being one of the processes that breeders have utilized most (Coors and Pandey 1999; Cumo 2016; Goulet et al. 2017; Kingsbury 2009). The onset of sugarcane breeding occurred more than a century ago, with the hybridization of ancestral sugarcane species and landraces, which has been thoroughly reviewed by other researchers. Here we will briefly address basic issues considered relevant to understand how breeders came up with the new type called EC (Alexander 1985).

Modern sugarcane cultivars are complex poly-, allo-aneuploid hybrids comprised by ~80% of *S. officinarum* genome (the sugary ancestor), 10–23% of *S. spontaneum* (the resilient ancestor), and 8–13% of recombinant or translocated chromosomes (D'Hont et al. 2008; Gouy et al. 2013; Moore et al. 2014; Piperidis et al. 2010). Such genetic structure brings the genomic equilibrium to the point that cane produces concomitantly high sugar and low fiber content, a combination alleged optimal for economical sucrose production (Jackson 2005; Santchurn et al. 2014). The said proportion provides the cultivars with adaptation to different agroclimatic conditions in the world, a characteristic which is mostly contributed by the ancestral *S. spontaneum* (Jackson 2005; Moore et al. 2014; Roach 1972; Selvi et al. 2005). However, the necessity to increase sugar content and concomitantly reverse the fiber content remains a crucial hindrance to the breeders, as it restrains the level of vigor and resilience necessary to allow a sustainable high yield (Botha 2013; Matsuoka 2016, 2017; Zhou 2013). A biomass crop is only feasible when it gives high productivity in order to not compete with the food crops for a scant land, to only mention one important debated concern (Fargione et al. 2008; Jakob et al. 2011; Levidow and Paul 2008; Miranda 2014; Nassar et al. 2008; Rosillo-Calle 2010; Thompson 2012; Tomei and Helliwell 2016). In other words, it should have enough resilience to produce satisfactory biomass yield in a land less appropriate for food production. Considering those premises immediately comes the idea of a plant with higher productivity and more resilience than conventional sugar cane (CSC). EC is a diverted sugarcane plant that conforms to this need. From the practical and end use perspective, it is a plant very much like sugarcane, which has a well-developed exploitation system, not only in the field but also in the industry (Schell et al. 2008), a crucial feature if a biomass crop is to be extensively adopted (Jakob et al. 2011; Long et al. 2015; Seebaluck and Leal 2015; Tammisola 2010).

3.4 The Fiber Alternative

Lignocellulose (fiber) is most abundant carbon-based product of photosynthesis in nature (Chen 2014; Cosgrove 2005; Frei 2013; Stitt 2013). It is composed of complex polysaccharides, cellulose, and hemicellulose, plus the polyphenol lignin, in distinct proportions depending upon the plant; in sugarcane, it reaches from 80% to 90% of the total dry matter (Chen 2014; Ferreira et al. 2013; Kim and Day 2011; Vassilev et al. 2011). Enveloping the cells, the polysaccharides play a key role in giving strength to them and regulating the turgor pressure as well as the water flow (Cosgrove 2005; Frei 2013; Jung et al. 2012; Stitt 2013); besides that, polysaccharides also provide the resistance to pests and diseases (Chen 2014; Rutherford 2014). Impregnating the xylem vessels are other polysaccharides, mainly lignin, thus forming the fiber, which not only gives the general structure to the plant, but it also supports the upward growth in tall plants (Buanafina and Cosgrove 2014; Chen 2014; Santanna et al. 2013). Hence, fiber is very important to an overall performance of a plant; in short, they give resilience to it.

Fiber-dedicated crops played a key role in the world agribusiness evolvement: cotton, wood plants, and pastures, to mention a few. Arguably, efficient fiber-producing plants are gaining additional importance nowadays, as they can serve to fix carbon in the aerial and underground structures and give clean bioenergy forms to help mitigate the hazardous GHG effects in the atmosphere (Aragon et al. 2013; Byrt et al. 2011; Ferreira et al. 2013; Goldemberg 2011; Haberl et al. 2011; Long et al. 2015; Somerville et al. 2010). As such, fiber-producing dedicated crops can be exploited to primarily produce heat by direct combustion and, subsequently, steam and electricity. Additionally, after industrial transformation, liquid combustibles such as ethanol, methanol, butanol, and oils, methane, or several other chemicals, pharmaceuticals, goods, etc. can be produced from such crops (Botha and Moore 2014; Lee et al. 2014; OECD 2014; Souza et al. 2013; Tomes et al. 2011;). Hence, sugarcane (*Saccharum* spp.) earns prominence for tropical and subtropical regions, mainly the EC type. As discussed in next sections, this type has no hindrances other biomass options still present to be adopted commercially (Zegada-Lizarazu et al. 2013). Alexander (1980, 1985) provocatively stated that the most remarkable feature of sugarcane is its overall capacity to produce biomass, with some species incidentally showing ability to accumulate sucrose. He added that exploiting the striking ability of sugarcane to produce total biomass using energy cane for bioenergy purpose would help the overall socioeconomic condition of a region or country.

3.5 Energy Cane in Context, and Its Current Status

Sugarcane breeding brought a steady increase in yield along the years in a long-time span, though modest in comparison with other crops (Burnquist 2013; Chudasama 2013; Gouy et al. 2013). However, in countries with a long history in sugarcane cropping, there is an increased claim that nowadays both the yield and sugar concentration in the stalk are very close to flat (Berding et al. 2004; Botha 2013; Dal-Bianco et al. 2012; Garside et al. 1997; Inman-Bamber et al. 2011; Jones and Singels 2015; Lingle et al. 2010). Several causes underlying the mechanism of this plateauing have been discussed (Burnquist 2013; Chudasama 2013; Dal-Bianco et al. 2012; Jones and Singels 2015), but a solution has not been approached (Botha 2013). Matsuoka (2016, 2017) reasoned that the tight range of fiber content established as a paradigm in CSC cultivars is what is hindering the yield increase. The abovesaid genomic composition of CSC hybrid cultivars in the order of 80% from *S. officinarum* and 20% from *S. spontaneum* brings a balanced trade-off between fiber content and sugar concentration in the juice, both for good milling and sugar recovery in the industry, whereas sustaining the necessary suite of agronomic characteristics.

Although the target of sugarcane breeding has always been high yield, both of cane and sugar, the strict trade-off has restrained elevated levels of vigor, resilience, and long ratooning, three main factors underlying sugarcane on farm yield (Matsuoka 2017). The result are cultivars with overall field productivity well below the attainable potential shown in the experiments (Irvine 1983; Moore 2005; Monteiro and Sentelhas 2017). For example, in Brazil, where active breeding programs were continuously releasing new cultivars (Machado Junior et al. 2015), the actual yield varied fourfold from the worst to the best yielding fields (rainfed conditions) according to the benchmarking data analyzed by Monteiro and Sentelhas (2017). Even restricting only to the State of São Paulo, where both the climatic conditions and the farming are reasonably good, a yield gap of 31% has been ascribed to farm management and 69% to water deficit. Low resilience explains most of such gaps. To overcome this faulty characteristic of sugarcane cultivars, the only measure is to increase the fiber content, which is brought by EC. High fibrous EC is expected to not only give a higher yield but a more even yield (stability) across sites and years (ratoons) due to its resilience resulting from the higher proportion of the genome of *S. spontaneum*, as advocated by Matsuoka (2017).

One of the most important plants' life survival strategies is a trade-off between some carbohydrates for reserve and the others for structural growth: prioritizing the reserve, the growth is sacrificed (Lambers et al. 2008). This trade-off explains the basic difference in biomass productivity between CSC and EC. In CSC, sucrose is prioritized as a reserve carbohydrate, whereas in EC the photosynthesized product is mostly diverted to structural function, i.e., cellulose, hemicellulose, and lignin (fiber). The strategy concerning EC is to increase fiber content in a higher level to withstand adverse growing conditions. That characteristic can be taken to advantage to produce biomass (Alexander 1980, 1985; Botha and Moore 2014; Giamalva et al. 1985; Tew and Cobill, 2008). Withdrawing the fiber restriction and consequently paying a penalty in terms of sucrose concentration, plant vigor and resilience are magnified, allowing a very high total biomass production per unit area, up to level never experienced by the traditional sugarcane-growing system (Alexander 1985; Bischoff et al. 2008; Giamalva et al. 1984; Matsuoka et al. 2014; Matsuoka 2017).

Considering the observed variation in terms of fiber and sucrose content in EC, Tew and Cobill (2008) devised two categories: Type I and Type II. They described the Type I as a cane closer to the CSC, with equal sucrose content but with somewhat higher fiber content, whereas the Type II refers to a cane with only marginal content of sugar and very high fiber content, aimed to be used exclusively for biomass production. Alexander's original proposal concerned only Type II cane, and both the lower sugar content and lower purity, combined with high fiber content, were significant contributors to the failure in its acceptance by traditional and conservative sugar mills. In fact, for this trade-off sugar–fiber level, several combinations can be developed. Thus, rather than considering EC as of two strict types, it would be more appropriate to treat it as a suite of combinations of sugar and fiber, high sugar–low fiber at one side and high fiber–low sugar at the other, with even more intermediary partitions than presented by Santchurn et al. (2014). EC can in fact be selected for multipurpose exploitation (Kennedy 2005; Matsuoka et al. 2014;

Ponragdee et al. 2013; Ramdoyal and Badaloo 2007; Rao and Weerathaworn 2009; Tew and Cobill 2008), from the more elementary burning to get heat, vapor, and electricity to various forms of goods, liquid combustibles (first-generation (1G) and second-generation (2G) chemicals), or even more value-added chemicals in proposed biorefineries (Arni and Converti 2012; Goldemberg 2011; Kim and Day 2010; Koller et al. 2012; Mulinari et al. 2012; OECD 2014; O'Hara et al. 2013; Rein 2007; Seabra and Macedo 2014; Villela Filho et al. 2011). The *Saccharum* genera belong to a complex botanical group which consisted of many genera: *Erianthus* sect. *Ripidium*, *Miscanthus*, *Narenga*, and *Sclerostachya* (Daniels and Roach 1987; Paterson et al. 2013; Roach and Daniels 1987). Genetic base broadening of the sugarcane population using these related genera has been suggested since the 1960s, and many programs have been conducting introgression with them (Dunckelman and Breaux 1972; Kennedy 2001; Lo et al. 1986; Miller et al. 2005; Sukarso and Mirzawan, 2005; Tai et al. 1992; Walker 1987). However, a very small fraction of all the available germplasm has so far been utilized, and almost invariably the aim has been to add vigor characteristics to sugar-producing varieties. The problem however is that making backcross to *S. officinarum* for two or three generations is inevitably necessary to get types conforming to the industry requirements which give as result a loss of vigor (Berding and Roach 1987; Lo et al. 1986; Roach 1972; Stevenson 1965; Tai et al. 1992; Walker 1987). Conversely, changing the selection pressures toward varieties that produce high biomass with less emphasis on sugar is an excellent alternative for exploitation of the wild germplasm (Alexander 1985), an issue scant explored in the past and does have much scope for progress (Bischoff et al. 2008; Kennedy 2005; Matsuoka et al. 2014; Matsuoka 2017; Ramdoyal and Badaloo 2007; Rao and Weerathaworn 2009; Ponragdee et al. 2013; Terajima et al. 2007; Tew and Cobill 2008; Wang et al. 2008).

The sugarcane breeding program of the University of Puerto Rico through Dr. T.L. Chu started a pioneering program selecting high biomass cultivars in 1978 (Alexander 1985; Samuels et al. 1984), and almost simultaneously, breeding programs in continental USA also took up the same idea, rescuing clones they had gotten from introgression program initiated in the 1960s (Eggleston et al. 2007; Hale et al. 2013). The joint Louisiana State University and the Houma-USDA program succeeded in producing some EC cultivars, and one of them, US79-1002, presented percentage of fiber as high as 28% and exceptionally high productivity. Five harvests of the variety from a single planting averaged 211 t ha^{-1} per harvest with continual yield increase from planted cane to fourth ratoon against 58 t ha^{-1} for a CSC cultivar (Giamalva et al. 1985). Later Bischoff et al. (2008) confirmed the high production capacity of the said variety reporting that it gave a steady linear increase in productivity, departing from 182 t ha^{-1} in plant cane to reach 247 t ha^{-1} in the fifth ratoon. It is necessary to mention here that the above cultivars as well as others released later in Louisiana are all Type I with characteristics to be managed under a short-growing cycle in temperate climate (Hale et al. 2013; White et al. 2011).

In Brazil, EC capacity to produce biomass can be duly exploited, as the climatic conditions to the development of sugarcane plants are more suitable than in temperate regions and the cycle can be extended to 12 months or more. Alexander (1985)

Table 3.1 Potential yield of EC cultivars in different regions of Brazil, average of plant cane, and first ratoon (Vignis, "unpublished")

Serial	Latitude	Longitude	State	Yield (t ha^{-1a})
1	10°22′47.51″S	36°55′36.84″W	Sergipe	159
2	17°32′04.17″S	51°04′48.31″W	Goiás	145
3	17°45′36.53″S	52°15′29.58″W	Goiás	182
4	18°47′51.46″S	53°01′43.11″W	Goiás	164
5	22°04′05.80″S	41°37′18.00″W	Rio de Janeiro	154
6	22°17′19.96″S	50°37′46.56″W	São Paulo	150
7	22°35′05.70″S	46°58′48.21″W	São Paulo	257
8	22°35′05.70″S	46°58′48.21″W	São Paulo	209
9	21°42′05.29″S	48°20′49.84″W	São Paulo	259

[a] t ha^{-1} = tons per hectare of total green matter (stalks and leaves)

had shown that the increase in biomass per unit time is higher in EC compared to CSC mainly in cycles over 12 months. As shown in Table 3.1, evaluation of the potential yield under dryland conditions in distinct latitudes from 10° to 22° South showed EC capacity to yield more than 250 t ha^{-1} (total green matter) as average of plant cane and first ratoon cycle at the best site. Also, the results evidence that the productivity varies according not only to the climate given by latitude and longitude but also to the soil type and other prevailing conditions, including management, in that specific farm and year. Even discounting 30% of those values, as usually perceived as a reasonable difference between farm and the experiment in Brazilian sugarcane cropping, the productivity is still the double of those being harvested through CSC in each of the locations. It is also noteworthy that the results were obtained from clones from the first cycle of the breeding program and the ongoing program is delivering clones with even higher potential.

Figure 3.1 shows that the potential productivity can increase from plant cane to first and second ratoons, a well-known characteristic of EC (Alexander 1985; Bischoff et al. 2008; Giamalva et al. 1984, 1985; Terajima et al. 2007; Tew and Cobill 2008; Wang et al. 2008). As consequence, the number of ratoons can be extended at least twofold that of CSC with no evident decrease in productivity (Bischoff et al. 2008; Burner and Legendre, 2000; León et al. 2010; Salassi et al. 2015).

Concerning total dry mass, Fig. 3.2 shows that in EC it is possible to break the upper limit of 30% of total dry matter usually referenced as a limit barrier in CSC (Botha 2013; Tew and Cobill 2008); most EC clones surpassed that limit, three of them going above 35%, supporting data presented by Giamalva et al. (1985), Kennedy (2008), and Kim and Day (2010), thus opening avenues to increase the dry matter productivity of EC.

Underlying the high biomass productivity of EC is what is called the "hidden half"—the root system (Waisel et al. 2002). Besides the well-known function of absorbing water and nutrient acquisition to sustain the growth of the aerial part and its own, the root system plays a role in the soil biota food webs, which is essential

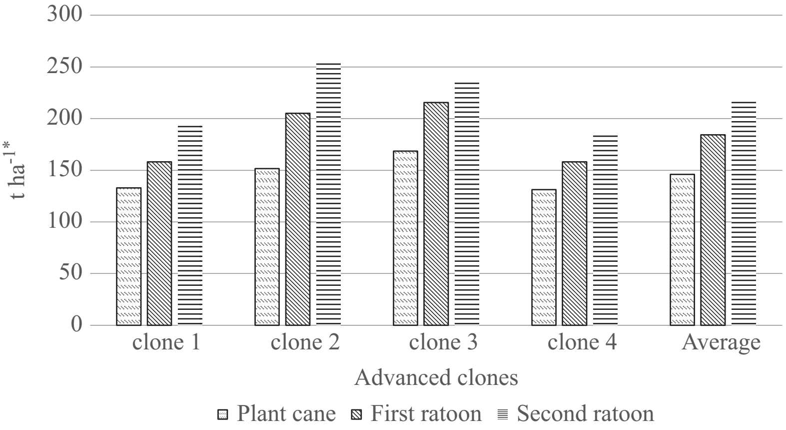

Fig. 3.1 Potential productivity of some EC clones across three harvest cycles under rainfed conditions in Brazil (∗t ha^{-1} = tons per hectare of total green matter)

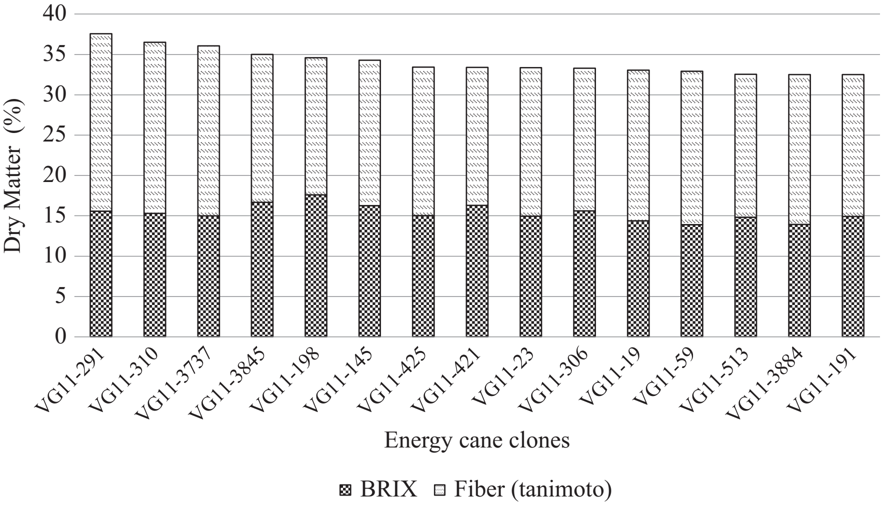

Fig. 3.2 Percentage of total dry matter (Brix + fiber) in stalks of selected EC clones

both for plants' growth and soil development (Gregory 2006; Voroney 2007). The root system of EC is much more profuse and vigorous than that of CSC due to the *S. spontaneum*'s contribution to this trait (Alexander 1985; Da Silva 2017; Matsuoka 2017; Matsuoka et al. 2014; Terajima et al. 2005), along with a striking feature of its property of bearing rhizomes (Alexander 1985; Legendre and Burner 1995; León et al. 2010; Matsuoka 2017; Matsuoka and Garcia 2011; Matsuoka et al. 2014; Panje 1972; Roach 1969, 1972). Rhizome is a structure inherited from the *S. spontaneum*, where carbohydrates are stored. It bestows the plant with perennialism and stress protection (Babu 1965; Brandes 1956; Daniels 1965; Murray 2013; Paterson 2009; Roach 1969). For CSC cultivars, the requirement of the binary high sugar–low fiber led to the dilution of *S. spontaneum*'s genome and, as result, the elimination of rhizomes. Roach (1969) reported the remote chance of combining the commercial attributes of *S. officinarum* with the rhizomatous habit of *S. spontaneum*, as this trait is lost after one or two backcrosses (Roach 1969, 1972). Sehtiya and Mehla (2012) also found that high-quality (high sugar content) canes had shallow roots, whereas middle to late maturing clones had deeper root system. Such results clearly fit to the dominance of genome of *S. officinarum* in the first case and, conversely, to a manifestation of genes of *S. spontaneum* in the second case. From the vigorous root system, associated with rhizomes, results both growth vigor and resilience in EC (Matsuoka 2016, 2017). Additionally, these characteristics allow EC to meet the demand for a much-needed soil regenerative crop plant nowadays. The vigorous, profuse, and profound root system gives better protection to the soil against erosion; favors rain water infiltration; mitigates downstream pollution by prejudicial substances like ammonium, phosphates, and potassium; and aids the soil microbiota. The profitability of the sugarcane cropping mostly depends on its ratoons: the higher the number of ratoons yielding above a threshold minimum, the higher the profit (Chapman and Wilson 1996; Kingston 2003; Salassi and Breaux 2002; Tonta and Smith 1996). The decrease in yield with the advancement of ratoons is accepted as an inevitable factor in sugarcane exploitation, and the growers' effort is to relieve it as much as possible with proper crop husbandry (Dharmawardene 2005; Matsuoka and Stolf 2012). For this reason, breeders set effort to select cultivars with good ratooning ability (Cox et al. 2000; Milligan et al. 1996; Mirzawan and Sugiyarta 1999; Skinner et al. 1987; Tripathi et al. 1992). However, this character is also inherited from *S. spontaneum* and, as explained before, the dilution of the genome of this ancestor in commercial sugarcane cultivars results invariably in the minimization of the attribute (Brandes and Sartoris 1936; Da Silva 2017; Jackson 1994; Matsuoka and Stolf, 2012; Panje 1972; Roach 1972). Conversely, in EC, the yield can be sustained for several ratoons, after some increase from plant cane to first and second ratoons (Alexander 1985; Bischoff et al. 2008; Burner and Legendre 2000; León et al. 2010; Salassi et al. 2015). Higher tillering ability has also been observed by several authors even in BC_1 clones. Legendre and Burner (1995) observed high tillering in BC_1 but not in BC_2 and BC_3, which denotes a dilution effect. Ramdoyal and Badaloo (2007) also confirmed a shift to characteristics inherited from *S. spontaneum* in F_1 families, high tillering included, as compared to BC_1 and BC_2.

A pioneer breeding effort to specifically develop EC was carried out by the now extinct sugarcane breeding program of The University of Puerto Rico in the 1980s of the last century (Alexander 1985) but had no continuity. However, from the long-lasting introgression effort done by the USDA's sugarcane breeding program since the 1960s, several EC types were selected for breeding purposes with some of them reaching final experimental status as EC (Giamalva et al. 1984, 1985; Hale et al. 2013; Knoll et al. 2013; Legendre and Burner 1995) and reaching variety status (Bischoff et al. 2008; Hale et al. 2013; White et al. 2011). Some released cultivars also come from materials dropped from the breeding lines due to a fiber content slightly higher than the standard value, or crossings purposely done for developing high fiber types (Hale et al. 2013; Sandhu and Gilbert 2017; Tew and Cobill 2008). Elsewhere, other breeding programs also have put some efforts in breeding high fiber or high biomass producing types, like in Barbados (Kennedy 2005), Mauritius (Santchurn et al. 2014), Japan (Terajima et al. 2007), and Thailand (Ponragdee et al. 2013), to mention a few.

In Brazil, EC breeding is being carried out for at least ten years. The pioneer effort was set by CanaVialis, a private company of sugarcane breeding (Matsuoka et al. 2012). Later, another private company was funded specifically to breed EC (Matsuoka et al. 2014). Soon thereafter, another company aiming to produce 2G ethanol from sugarcane debris also started an EC breeding program (Santos et al. 2016). Today, only the first two are running, whereas traditional sugarcane breeding programs are eventually carrying selections of biomass-type clones (Silveira et al. 2016). Concerning commercial adoption of EC, it is in infancy. Cultivated area in Brazil surpassed 8000 ha as of 2017, and the total feedstock delivery (fresh mass) is projected to surpass 1,000,000 tons in 2018 (Vignis, “unpublished”). To our knowledge, it is the only case of commercial exploitation of EC in the world. The main purpose of that feedstock is still to get bagasse for boilers in sugarcane mills, and processing plants of soybean, corn, and citrus. In one case, a mill that stayed closed for 2 years due to shortage of CSC feedstock reopened to mill exclusively EC, aiming to produce 1G ethanol, and eventually VHP, besides taking advantage of an increased amount of bagasse (Ramos 2017). Another case is a project considering substituting coal through bagasse in a big cement-producing plant.

One of a critical issue concerning EC feedstock is the knowledge on details of its chemical and mineral composition. Excluding rare studies, most of analyses to date have limited to the determination of traditional parameters in a sugar mill. Table 3.2 brings results of analyses of two EC clones compared to the most planted CSC cultivar. Striking differences between EC and CSC are the higher fiber content, and conversely the lower sugar content (Brix and pol) and purity of the former, added by a slight higher content of simple sugars. Absolute numbers differ with some in literature, as the components may vary according to several factors, especially the clones per se age, soil, climatic conditions, etc. (Santos et al. 2016).

In terms of chemical composition, what can be observed from the data on Table 3.3 is that there is not any conspicuous difference between EC and CSC, except a slightly higher content of ash. Fiber analysis done in American EC cultivars also revealed similar range of concentrations for cellulose, hemicellulose, and lignin (Kim and Day 2011; Warp and Sandhu 2017). Ogata (2013) analyzed 207 high fiber genotypes and found great variation in terms of cellulose (26.47–54.10%), hemicellulose (16.7–25.9%), and lignin (17.7–27.13%). Such results show that the breeders have at hand a great variability to manage according to specific feedstock composition needed by the industry.

Table 3.4 presents results of comparative analyses of CSC and EC, both in an integral form and after pressing the juice, i.e., in bagasse form. Again, no significant differences were observed in any comparison, except a higher content of ash in EC

Table 3.2 Comparative composition of two EC clones and a CSC cultivar according to CSC mill's analysis (Vignis, "unpublished")

Component[a]	EC1	EC2	CSC
Humidity	71.80	70.00	70.00
Fiber % cane	14.01	16.25	11.28
Brix cane	14.19	13.32	17.82
Pol % cane	10.96	10.55	15.12
Juice purity	77.00	79.20	84.85
Red. sugars % cane	0.70	0.59	0.54
Total sugars % cane	12.84	12.40	17.23
Total sugars purity % cane	90.49	93.09	96.69
Extraction (mL kg^{-1})	580	640	680
pH juice	5.50	5.40	5.60
Brix juice	16.50	15.91	20.10
Pol % juice	13.40	13.43	17.64
Juice purity	81.00	84.40	87.80
Total recoverable sugars	117.46	113.42	157.62

Topped and detrashed stalks

[a] All results in %, except extraction, pH, and total recoverable sugars (g kg^{-1} of cane)

Table 3.3 Results of chemical analyses of three EC clones compared to a widely grown sugarcane cultivar (RB867515) (Vignis, "unpublished")

Component[a]	EC 1	EC 2	EC 3	CSC
Humidity	64 ± 4	64 ± 4	64 ± 4	71 ± 4
Fixed Carbon	15.32	15.27	14.56	15.91
Carbon	47.19	46.65	47.18	45.76
Hydrogen	6.14	6.16	6.13	6.21
Nitrogen	0.4	0.4	0.4	0.4
Ash	2.68	2.73	2.44	2.09
Sulfur	0.10	0.09	0.12	0.08
Volatiles	82	82	83	82
Oxygen	43.49	43.97	43.73	45.46
Gross Calorific Value	18.8	18.7	18.8	18.4
Net Calorific Value	17.5	17.4	17.5	17.1
Cellulose	45.5 ± 1.8	42.0 ± 2.4	42.2 ± 0.3	40.6 ± 0.7
Hemicellulose	25.3 ± 1.1	25.2 ± 0.5	24.0 ± 1.2	20.9 ± 0.9
Lignin	17.9 ± 0.3	18.4 ± 0.2	18.7 ± 0.3	13.8 ± 0.1
Hemicellulose	25.3 ± 1.1	25.2 ± 0.5	24.0 ± 1.2	20.9 ± 0.9
Acetyl group	1.9 ± 0.1	1.9 ± 0.1	2.0 ± 0.1	1.6 ± 0.2
Extractives	23.8 ± 1.1	23.7 ± 0.1	23.4 ± 0.8	36.9 ± 0.1
Ash	3.4 ± 0.2	2.9 ± 0.0	2.4 ± 0.1	2.1 ± 0.1

[a] All values in percentage, except GCV and NCV in MJ kg^{-1}

Table 3.4 Results of component analyses comparing integral and dried feedstock, and moisture-containing and dried bagasse of CSC and EC (Vignis, "unpublished")

	Integral feedstock		Dry feedstock		Bagasse		Dry bagasse	
Component[a]	CSC	EC	CSC	EC	CSC	EC	CSC	EC
Moisture, total	76.86	74.77			52.80	52.65		
Ash	1.19	1.90	5.15	7.55	1.72	4.08	3.64	8.62
Volatile matter	18.86	19.70	81.51	78.09	39.69	37.10	84.09	78.35
Fixed Carbon	3.09	3.63	13.34	14.36	5.79	6.17	12.27	13.03
Sulfur	0.05	0.03	0.20	0.10	0.01	0.07	0.03	0.15
Gross Calorific Value	1807	1915	7811	7590	3745	3530	7933	7456
Carbon	10.07	10.91	43.50	43.25	20.88	19.58	44.23	41.36
Hydrogen	1.35	1.23	5.82	4.89	2.71	2.51	5.74	5.31
Nitrogen	0.07	0.19	0.28	0.74	0.08	0.10	0.17	0.21
Oxygen	10.41	10.97	45.05	43.47	21.80	21.01	46.19	44.35
Chlorine	0.120	0.25	0.517	0.99	0.026	0.094	0.055	0.199
Sulfur, Pyritic	<0.01	<0.01	<0.01	<0.01	0.01	<0.01	0.03	<0.01
Sulfur, Sulfate	0.10	0.03	0.10	0.11	<0.01	<0.01	<0.01	<0.01
Sulfur, Organic	0.02	<0.01	0.10	<0.01	<0.01	<0.01	<0.01	0.019

[a] All values in percentage, except GCV in MJ kg^{-1}

compared to CSC, either in integral form or as bagasse. Although the calorific value was not distinct, it is interesting to remark that in one commercial test with a fluidized boiler, it was observed that both the uniform granulometry and moisture of EC bagasse allowed a good combustion stability.

Table 3.5 shows data of analyses of ash components, as this information can be useful for some specific end products. The values for several constituents are quite distinct between CSC and EC, highlighting the higher silica content in EC and its bagasse compared to CSC, and the lower concentration of aluminum in the same comparison. However, the numbers in Tables 3.2, 3.3, 3.4, and 3.5 should be taken cautiously and only as a general reference; the variation could be great if considering all the available genetic range, and also, readings can be affected by the methods of analysis.

3.6 Discussion

The potential productivity of sugarcane is theoretically nearly 400 tons of fresh biomass per hectare per year in optimum conditions, or around 240–280 tons in good experimental conditions (Alexander 1985; Bull and Glasziou 1975; Irvine 1983; Waclawovsky et al. 2010). High potential, however, does not mean high and reliable yields at the farm level (Duvick and Cassman 1999). In the field, the cultivar is subject to several stressors continuously, either by the deficiency of the environment per se or by the inadequate farm management practices. The resilience of

Table 3.5 Comparative analysis of ash components of integral CSC and EC and bagasse of both feedstocks

	Integral		Bagasse[a]	
Item	CSC	EC	CSC	EC
Silicon dioxide	49.75	57.86	70.72	80.24
Aluminum dioxide	5.28	3.43	11.62	7.18
Titanium dioxide	0.47	0.41	0.68	1.08
Iron oxide	2.40	1.86	5.58	3.15
Calcium oxide	6.52	8.03	2.49	1.79
Magnesium oxide	6.92	3.74	1.99	0.69
Potassium oxide	17.98	16.54	3.32	4.08
Sodium oxide	0.59	1.10	0.54	0.09
Sulfur trioxide	7.30	3.99	1.67	1.04
Phosphorus pentoxide	2.46	2.66	1.14	0.56
Strontium oxide	0.05	0.05	0.03	0.02
Barium oxide	0.07	0.05	0.05	0.02
Manganese oxide	0.21	0.28	0.17	0.06
Silica value	75.85	80.93	87.55	93.44
Base acid ratio	0.62	0.51	0.17	0.11
Fouling index	0.59	1.10	0.09	<0.01
Type of ash	Lignitic	Lignitic	Bituminous	Bituminous

[a] All values in percentage

commercial sugarcane cultivars is limited. This is why the world commercial average productivity is less than 50% of the attainable value (Alexander 1985; Irvine 1983; Monteiro and Sentelhas 2017; Waclawovsky et al. 2010).

Due to the low field performance of sugarcane, the paradigm of a feedstock easy to be milled and exclusive to produce sugar was challenged by A. G. Alexander (1980, 1985) in Puerto Rico in the 1980s: for almost a decade, he persevered in a crusade to convince people that exploiting the fiber side of the plant, instead of the sugar, would result in a much more profitable industry. But, his "EC management system" was rejected at that time because breaking a very ingrained concept of having the sugarcane plant as only a sucrose producer was literally a battle (Matsuoka et al. 2014). The high potential productivity of EC across several ratoons, due to both its vigor and resilience, in a level of two- to threefold that of sugarcane, is an unprecedented achievement in CSC exploitation, thereby constituting a breakthrough technology to the sugarcane cropping and industrialization. In this sense, this crop can finally equal cereal crops in terms of gain achieved by breeding in the so-called "Green Revolution" (Borlaug 2003; Kingsbury 2009). However, the fundamental difference of this new plant, a producer of fiber instead of sucrose, remained a serious barrier in its adoption.

For most part of the world, wastes from agriculture, mainly comprising crop residues and wood, can be used to produce bioenergy in various forms. Distinct usages can include household heating, producing vapors, gas, electricity, etc. Although such alternatives have their own value for specific regions or conditions, it can be argued that they don't have enough density to significantly contribute in an overall energy matrix. To this end, specialists recognized that it is necessary to relay in sustainable dedicated crops with high biomass productivity (Byrt et al. 2011; Jessup 2011; Somerville et al. 2010; Stitt 2013).

Concerning dedicated crops, many distinct options have been studied, each one being proposed for specific countries according to their general infrastructure and demand, available lands, stage of technological development, and agroclimatic conditions (Byrt et al. 2011; Jessup 2011; Long et al. 2015; Somerville et al. 2010; Stitt 2013; Viator et al. 2010; Zegada-Lizarazu et al. 2013). Most of them, however, require variable levels of tailoring of several factors including breeding, propagation processes, farming, harvest, delivery, storage, and processing, i.e., modulation of entire production chain from field to industry (Seebaluck and Leal 2015; Tammisola 2010; Zegada-Lizarazu et al. 2013). Conversely, EC requires minimal adaptations (Aragon et al. 2013; Giamalva et al. 1985; Kim and Day 2010), as it is quite like sugarcane, a millenary crop with a well-known technology of production and industrialization (Alexander 1985; Botha and Moore 2014; Long et al. 2015; Tammisola 2010). Moreover, its feedstock can be harvested and delivered almost year-round, a characteristic also needed to be valued as a biomass.

Land use and competition with food production are two major concerns concerning bioenergy crops. Such reservations have been raised even in countries like Brazil, where much land is still available for both biomass and food production (Goldemberg and Guardabassi 2010; Manzatto et al. 2009; Neves et al. 2011; Rosillo-Calle 2010; Woods et al. 2015; Zuurbier and van de Vooren 2008). Brazil is a large producer of most agricultural products as well as timber (Fischer et al. 2008; Neves et al. 2011; OECD-FAO 2015). Additionally, animal-derived foods like meat, milk, and dairy products come mostly from pastureland in the country, which represent a substantial portion of exploited land usually under poor technology (Manzatto et al. 2009; Nassar et al. 2008). A great part of the huge expansion of sugarcane crop in Brazil, in the last 40 years, was over pastureland (Bacha 2011; Fischer et al. 2008; Nassar et al. 2008), or "cerrado"—a Brazilian savanna biome, except in cases like in the State of São Paulo where sugarcane displaced grain crops, firstly, and pastureland, secondly (Miranda 2014; Mueller and Martha Jr 2011; Nassar et al. 2008). São Paulo is now the largest producer of sugarcane among Brazilian states. Hence, although land competition between energy crops and food crops is not of a high concern in Brazil, it still deserves attention and careful analysis, especially in other countries where situation is not same. To this end, EC can give significant contribution. Owing to its high productivity, the requirement of land is not so overwhelming. For example, it has been calculated that substituting sugarcane by EC in the present land area utilized in Brazil to produce ethanol (~five million hectares), the country can fulfill the goal of 50 billion liters in 2030 targeted to meet the commitment signed in COP21 without requirement of any additional land (Rubio L.C., "unpublished data"). However, this calculation includes the production of 1G ethanol from the juice and 2G ethanol from the bagasse and leaves, for which the technology is still evolving and not completely deployed.

Although sugarcane agroindustry evolved to primarily exploit its sucrose, now time has come deemed imperative to exploit its entire plant biomass. As stated by Alexander (1985), the genera *Saccharum's* proficiency is to produce structural carbohydrates, instead of sucrose. If the world is urgently needing alternatives of renewable energy to decarbonize the atmosphere, as most of the nations recognized in the recent summit COP21 in Paris (UNFCCC 2016), sustainably produced biomass can play a role. Among the proposed dedicated biomass crops, sugarcane is widely recognized as a the most suitable option as it does not only have a high biomass productivity, but also well-established systems of agricultural production, transport logistic, and industrial processing (Alexander 1985; Long et al. 2015; Ming et al. 2006; Moore et al. 2014; Waclawovsky et al. 2010). Moreover, it can be disposed almost all the year round, and it complies with most of the requirements considered necessary to favorably meet environmental issues (Amaral et al. 2008; Goldemberg et al. 2008; Singh 2013; Souza et al. 2015; Zuurbier and van der Vooren 2008).

Therefore, EC is a unique biomass crop for tropics and subtropics when considering the entire production and industrialization chain (Zegada-Lizarazu et al. 2013). Its field production system, as well as harvest and delivery processes, is very much like the traditional sugarcane production system, only needing minor adaptations to the machines due to its high productivity, as well as in the processing system to mill a high fiber content feedstock (Alexander 1985; Aragon et al. 2013; Botha and Moore 2014; Long et al. 2015). Another critical issue to a successful exploitation of biomass as a bioenergy crop is its availability for a year-round processing (Kim and Day 2010), which is not possible in most alternatives proposed as biomass crops, thus challenging the development of an optimal supply chain (Seebaluck and Leal 2015; Zegada-Lizarazu et al. 2013). Conversely, EC can be delivered almost year-round in tropical and subtropical conditions, only requiring some small stockpiling adjustment to the feedstock availability in short periods of rainy days when the harvest and hauling is not possible.

To the traditional sugarcane industry, EC cannot be viewed as a competitor but rather as an add-in crop in a new platform of production-industrialization aimed to bring sustainability to this old and instable crop-industry complex (Matsuoka 2017). Global scale studies show a wide area available for energy crops, if considering those prone to be grown in less favorable environment, mainly in Brazil and in the sub-Saharan Africa (Fischer et al. 2008; Strapasson 2014; Woods et al. 2015). Although the numbers are controversial, roughly 100 Mha of suitable land is an agreeable number for such land, and Brazil has at least 60% of the mentioned area (Manzatto et al. 2009, Long et al. 2015; Matsuoka 2017; Souza et al. 2013; Strapasson 2014). CSC is admittedly a biomass crop that could significantly contribute to the reduction of C footprint of the planet. However, this prospect is considering a substantial increase in its productivity in the years to come, which is only an expectation this time (Long et al. 2015; Souza et al. 2013; Strapasson 2014). Matsuoka (2017) affirmed that EC can meet such expectations and targets. As such, currently, EC is an innovative and disruptive technology the sector can now experience. Although emphasis is being given here to the tropics and subtropics, by no means it is to exclude temperate regions. As has been said, the USA is where EC was firstly developed, and most of studies with this plant have been successfully done there, including those concerning economic feasibility (Salassi et al. 2015; Viator et al. 2010).

Brazil is home to the world's largest sugarcane crop area as well as to the production of sugarcane-derived ethanol. Nearly five million hectares are dedicated to ethanol production; however, much more land is still available without needing land clearing (Manzatto et al. 2009). Therefore, it can give a definite contribution toward the world's much-wanted cleaner fuels. Keeping that in view, EC exploitation has already begun in Brazil. It is expected that the cultivated area will expand at a significant pace to eventually establish EC as a new crop, not only in Brazil or the USA but also in other countries. Producing the needed amount of feedstock in less area or producing higher amounts in the same area is a benefit not only with economical but also with environmental and social impacts. Besides, with EC comes the possibility of transforming the old and always instable sugarcane industry into biorefineries to produce many distinct products with high added values the modern civilization needs, at the same time addressing pressing environmental issues (Eggleston and Lima 2015; Schell et al. 2008).

One of the first innovations in biomass utilization is the production of (2G) chemicals—2G ethanol is one of them. Pilot or semi-commercial plants of 2G ethanol started to operate in EU, Canada, and EUA some years ago, and few are still operating (Manzer 2013). Smoothly operating an innovative technology's plant is not always easy. Industries have already been launched to use CSC trash and bagasse. Although they are still in their learning curve, it is expected that obstacles will progressively be resolved, thereafter opening a large window for EC utilization (Bonomi et al. 2016; Carvalho-Netto et al. 2014; Janssen et al. 2013; Junqueira et al. 2017; Manzer 2013; Muktham et al. 2016; Santos et al. 2016). Furthermore, EC, besides its agronomic performance, allows an advantageous integration of 1G and 2G technology. Hence, 1G ethanol can be produced from its juice, and 2G ethanol or other 2G chemicals can be yielded from its leaves and bagasse. This integration has been shown to significantly reduce the cost of ethanol to a level that could make it definitively competitive with gasoline in any projected price of petroleum in a long run (Dias et al. 2016; Junqueira et al. 2017; Milanez et al. 2015). As many other processes of biomass transformation are already under development, it is expected that EC will definitively be established as a biomass crop in Brazil (Eggleston and Lima 2015; Gupta et al. 2014; Koller et al. 2012; Mulinari et al. 2012; Villela Filho et al. 2011). Thereafter, the example can be mirrored to other countries, especially of Sub-Saharan Africa and Southeastern Asia where EC is expected to have huge potential (Afionis et al. 2016; Fischer et al. 2008; Strapasson 2014).

3.7 Conclusion

Biomass as a renewable energy source is one alternative to aid the world's sturdy and urgent necessity to depart from fossil fuels' dependency. In spite of considerable efforts by the research and technological community in the last decades to move forward in that end, still it stands as a minor figure in the world's perspective.

Among several kinds of biomass feedstocks, specialists point out that only dedicated crops can duly contribute with the necessary volume, and among them, sugarcane stands out as a unique and real option, at least in tropical and subtropical regions. However, there is also recognition that the robustness of this option depends on a substantial increase in its productivity. Here resides the problem. Average world productivity of CSC reached a yield plateau and remains stagnant in the last decades, notwithstanding continuous breeding efforts and both field and industry management advancements. Shifting to EC is considered a dependable measure to overcome that barrier, as it is a plant with possibility to double the biomass production per unit of land area, mainly the fiber portion. The possibility in medium term of producing 1G ethanol from EC juice and simultaneously 2G ethanol from its bagasse and trash brings an enormous additional advantage over other biomass options. The exploitation of this crop will therefore permit a dependable reduction in the cost of production of biomass energy, being it as liquid combustible, heat, steam, or electricity, and not compromising too much the precious agricultural land area. Moreover, very importantly, its adoption can be done with minor adjustments to the well-known production practices of CSC, both in the field and in the industry. In the long run, it will be an adequate feedstock for future biorefineries producing other biofuels like biooils, jet fuel, and building-block chemicals to be used as feedstocks to reach several advanced products and goods.

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Chapter 4
Genetically Modified Sugarcane for Biofuels Production: Status and Perspectives of Conventional Transgenic Approaches, RNA Interference, and Genome Editing for Improving Sugarcane for Biofuels

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4.1 Introduction to Sugarcane as a Bioenergy Crop

Sugarcane has recently earned importance as an imperative bioenergy crop (Khan et al. 2017a). Approximately 21% of the sugarcane production is being used for biofuel production besides its role in cogeneration of thermal and electrical energy at the sugar mills (OECD-FAO 2016). Apart from first-generation ethanol, sugarcane is also an excellent source of lignocellulosic biomass, which can be utilized for second-generation ethanol engenderment. As an energy crop, sugarcane can help in reducing the dependence on oil-seed-based bioenergy, which is generally derived from the food crops otherwise and gives rise to food vs. fuel issues (Bewg 2015).

Sugarcane is one of the most efficient plants for converting sunlight energy into chemical energy, which can further be used to produce biofuels (Lu and Mosier 2008). Attributed to its C4 photosynthetic system, sugarcane yields huge biomass per unit area, making it an ideal feedstock (Suprasanna et al. 2011). It is among the list of agricultural commodities having the highest energy output-to-input ratio (Heichel 1973). For instance, in Hawaii, the energy output/input ratio of sugarcane is 3:1 (Tew 1980). Whereas for locations like Brazil, output/input ratios as high as 8:1 have been observed. On the other hand, the same proportion for corn fall around 1.25:1 only (Hill et al. 2006; Lam et al. 2009). Additionally, another feature which makes sugarcane a choice for biofuels and bioenergy is the anticipation that its production is sustainable in reference to ethanol as well as carbon efficiency (Maldonado et al. 2010).

Brazil ranks first in total sugarcane production followed by India, China, Thailand, and Pakistan (FAOSTAT 2015). With increasing demands for biofuels

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because of environmental concerns, limited natural fuel resources, and the success of Brazilian ethanol program *ProAlcool*, ethanol production is becoming an important component of the sugarcane sector. It is estimated that the production of ethanol only in Brazil will rise to 65 billion liters by 2020 (Matsuoka et al. 2009).

Biofuels face certain reservations primarily because of the concerns related to food security. Second-generation biofuels address the issue, but the technology for their production is not mature yet (Khan et al. 2017c). Therefore, it is direly needed to introduce new sugarcane cultivars which could break the sugar content ceiling for addressing our sugar and energy needs at the same time and could make the second-generation biofuels a reality (Khan et al. 2017b). Genetic engineering, in such a scenario, is a vital strategy to express desirable traits in cane genotypes (Butterfield et al. 2002).

Genetic manipulation of sugarcane is very laborious when compared against the genetic engineering of other crops. However, with the sequencing of sugarcane genome being completed recently, developments in its transcriptomics and proteomics, and new advances in current genome editing technologies, sugarcane improvement through transgenesis is expected to progress at a rapid pace (Dal-Bianco et al. 2012; Garsmeur et al. 2018). On optimistic side regarding genetically modified (GM) sugarcane production and multiplication, sugarcane does not produce viable pollens in many areas of its cultivation—and thus it can provide a high level of transgene clones (Taparia et al. 2012a).

GM sugarcane is an answer to many of the targets in sugarcane crop production including biotic and abiotic stress tolerance, enhanced yields per unit area, and augmented sugar contents. All such characteristics can make sugarcane and cane fuel engenderment more practical, profitable, and cost-effective.

4.2 Need to Adopt Transgenic Approaches

The human population is on the rise, and requirements for food and other necessities are increasing every passing day (Maldonado et al. 2010). Natural food and fuel resources are declining, putting more pressure on breeding practices to fulfill the human requirements through better crop varieties. Fortunately, the revolution of genetic knowledge has opened new avenues in crop improvement. It has equipped scientists with novel tools to combat the recent and alarming challenges regarding agricultural production. Realizing the need of the hour, various countries including the United States and China are now spending billions of dollars to investigate and develop GM crops to address challenges against crop production (Khan et al. 2018; Maldonado et al. 2010; Stone 2008).

Remarkable improvements are required in bioenergy crops including sugarcane to ensure sustainable production (Metzcalf and Hedin 2007). Enriching sugarcane through traditional breeding is an extremely laborious, intricate, and time-consuming process because of its perennial nature and limitations related to flowering and hybridization. Sugarcane is a highly polyploid crop having around 5–14 copies of the alleles in its genome, which makes it difficult to change the phenotypic expression expecting to replace all the poor alleles with the desirable ones. Hence, simple Mendelian heritability rules do not predict the actual outcomes in sugarcane and segregation statistics of polyploid plants must be used (Henry and Kole 2010).

Selection in sugarcane breeding starts by crossing two parents in a hope to attain a desirable genetic combination in some of the progeny plants. Typically, sugarcane selection work starts with 100,000 seedlings, whereas a cane variety is released after 10–12 years of evaluation (Malik 2010). Because of decades-long breeding efforts to select for the same traits of interest, we are already left with limited genetic resources, and therefore, sugarcane breeding has been very slow since last decade. Keeping in view of the current status, it is estimated that sugarcane is approaching the yield and sugar content ceiling and now it may become obstinate to surpass the physiological and metabolic barriers for enhancing these parameters through conventional approaches (Gilbert et al. 2008; Maldonado et al. 2010; Shanthi et al. 2008).

Therefore, conventional approaches of sugarcane breeding are not sufficient to meet the increasing demands of ethanol and sugar. Hereafter, it is inevitable to explore transgenic approaches for sugarcane improvement to fulfill the world's sugar and energy demands. Transgenic strategies introduce one or few traits of interest in a sugarcane clone without disturbing other, already selected, commercial attributes. Such transformational methods have a great potential to bring about remarkable changes in traits of interest apart from saving time and costs required otherwise to acquire minor improvement (Maldonado et al. 2010). Moreover, fewer plants need to be evaluated for improving sugarcane through transgenic approaches.

Recent developments in gene expression profiling and functional genomics are opening new vistas regarding GM sugarcane production. First transgenic sugarcane was developed by Bower and Birch (1992). Since then, plentiful attempts have been successful in introducing various traits of interest in sugarcane. Numerous genes have been transformed successfully and the achievements in sugarcane transgenics are increasing as we get new insights into its functional genomics and expressions profiles, and modern transformational technologies. First GM sugarcane has been approved by Indonesia for commercial cultivation (Parisi et al. 2016), whereas Brazil has also approved GM sugarcane in 2017 (Reuters 2017). Moreover, a number of transgenic lines are in pipeline in other countries (Mohan 2016).

4.3 Mechanism of Sugarcane Transformation

Several strategies have been endeavored for sugarcane transgenesis, resulting in variable success. However, efficient sugarcane transformation has been reported through electroporation, chloroplast transformation, microprojectile delivery, and *Agrobacterium* (Ithape et al. 2017; Rani et al. 2012). For *in planta* genetic transformation, axillary buds, shoot tip explants, cane seeds, and young leaf whorl have been utilized (Khan et al. 2013; Manickavasagam et al. 2004; Mayavan et al.

2013). Although production of transgenic plants using both the suspension culture and in vitro somatic embryogenic callus has been reported, the latter one is preferred for its high regeneration potential (Alcantara et al. 2014; Efendi and Matsuoka 2011; Kumar et al. 2014b; Taparia et al. 2012b).

Attempts of production of sugarcane transgenics have remained focused on improving the sucrose contents (Botha and Groenewald 2001; Vickers et al. 2005), production of novel sugars (Ithape et al. 2017), resistance to sugarcane viruses (Gilbert et al. 2005, 2009), borer resistance (Gao et al. 2016), salinity and drought tolerance (Saravanan et al. 2018; Wang et al. 2005), and herbicide resistance (Kumar et al. 2014a; Reis et al. 2014). All these parameters directly or indirectly relate to higher crop performance which would lead to greater sucrose, ethanol, and biomass production. Augmenting these characteristics can enhance the engenderment of first- and second-generation biofuels from the cane industry and make the crop as well as industrial production of ethanol highly cost-effective.

Engineering the cellulosic material of sugarcane for limiting the lignin content is another aim of sugarcane transgenics for economically feasible lignocellulosic biofuels (Weng et al. 2008). Even more, transgenic sugarcane approaches are targeting production of various industrial products, adopting the concept of biorefinery for sugarcane. These include naturally occurring compounds for bioplastics, functional foods, biopolymers, biopigments, industrial enzymes, and pharmaceuticals (Grice et al. 2004; Manickavasagam et al. 2004; Mitchell 2011; Suprasanna 2010; Wang et al. 2005).

The following are the major methods and techniques which have been used for producing GM plants, including sugarcane.

4.3.1 Electroporation

Electroporation is a well-established method of transformation in which high voltage makes the cells to be transfected electropermeabilized and then the foreign DNA is introduced into the plant genome through these pores (Weaver and Chizmadzhev 1996). Arencibia et al. (1995) effectively used this approach to genetically transform commercial sugarcane varieties by inducing DNA into embryogenic calli. The confirmation of transgenics was done through GUS staining and Southern Blot. The greatest advantage of electroporation over other methods is the fact that all the cells subjected to electroporation are in same physiological state after transformation.

Various factors which determine the success of electroporation include the electric field intensity, characteristics of the applied pulses, and the electroporation medium (Gallois et al. 1995; Singh et al. 2013). This method has been used by several researchers for transforming sugarcane (Arencibia et al. 1995; Chowdhury and Vasil 1992; Rathus and Birch 1992). It is an inexpensive and simple approach as compared to other cane transformation methods. However, in spite of many advantages, the use of electroporation for sugarcane has been limited because of the unavailability of reliable approaches for plant regeneration from protoplasts. Also, generally thick cell walls of the sugarcane present a physical hurdle toward success of this procedure. Although Srinivasan and Vasil (1986) reported success in overcoming such issues, reproducibility for such regenerations has been low, presenting a challenge to sugarcane improvement through electroporation (Singh et al. 2013).

4.3.2 Chloroplast Transformation

Chloroplast transformation is a promising approach as the gene of interest is integrated into plastids in this system. For this transformation, protoplast-mediated or microprojectile methods of delivery can be adopted; however, chloroplast-specific vectors are required for efficacious results (Barampuram and Zhang 2011).

Chloroplast has a highly conserved genome, comprising of double-stranded DNA of around 120–220 kb. The chloroplast DNA is organized as linear molecules or monomeric circles. Chloroplast transformation system consists of target-specific flanking sequences and expression cassettes which integrate into the target through homologous recombination (Maliga 2004). In spite of the fact that chloroplast transformation has been reported since 1988, the technique still needs to undergo improvements especially for higher plants like sugarcane (Boynton et al. 1988; Scortecc et al. 2012).

Plastid genes are inherited maternally; therefore, this transformation system can be employed to express many genes like a polycistronic unit; problems such as position effect and transgene silencing can also be easily tackled in this transformation system (Barampuram and Zhang 2011; Daniell et al. 2005). However, in spite of such advantages, the system is yet incipient even for C3 monocots and its practical success in C4 plant like sugarcane has been limited (Singh et al. 2013). Yet, chloroplast transformation offers greater biosafety, maternal transfer, and higher product yields and therefore positions as a potential technique to be explored for sugarcane improvement to target sugar or energy traits (Scortecc et al. 2012).

4.3.3 Biolistic Transformation

Biolistic transformation is a versatile technique which has been widely used for sugarcane. It works on the principle of employing extremely high-velocity microprojectiles to deliver DNA into the recipient cells. Using precipitation with spermidine or calcium chloride, DNA of interest is first coated on micron-sized gold or tungsten particles. Later, biolistic (gene) gun is employed to accelerate the particles, making them enter the target cells. Once the DNA is in the nucleus, it gets incorporated into the host chromosomes, resulting in transgene expression (Kikkert et al. 2005; Sanford et al. 1987).

This method of transformation can even bring about the modification in tissues in situ. For transforming sugarcane, the biolistic approach can be applied in embryogenic callus, as well as meristems (Bower and Birch 1992; Snyman et al. 2006). Biolistic transformation also has an advantage of the possibility of co-transferring multiple and unlinked transgenes (Altpeter et al. 2005). The technique has served various transformation studies in sugarcane (Altpeter and Oraby 2010). However, the success rate is dictated by efficient callus production and plant regeneration (Kaeppler et al. 2000; Scortecc et al. 2012). It is a robust and simple methodology which has been extensively exploited in transforming sugarcane although, sometimes, it can lead to complex transgene integration which causes issues in later analysis and can result in transgene silencing (Hotta et al. 2010; Suprasanna et al. 2011).

Biolistic transformation in sugarcane has undergone various improvements over time. Usually, this method uses indirect somatic embryogenesis, which necessitates time-consuming tissue culture practices (Gallo-Meagher and Irvine 1996). Additionally, in tissue culture, plants can undertake changes because of somaclonal variations as well (Khan et al. 2017b; Taparia et al. 2012a; Vickers et al. 2005).

Taparia et al. (2012a) successfully used minimal expression cassette approach for genetic transformation of sugarcane through gene gun. Such expression cassettes not only simplify the gene delivery, but they also efficiently get integrated as they don't contain the prokaryotic backbone which would induce methylation on integration (Jakowitsch et al. 1999). Through this approach, Taparia et al. (2012a) developed transgenic sugarcane plants for transplantation to soil only in 12 weeks. Such a brisk approach would not only result in stable transformation, but it also leads to fewer chances of somaclonal variations.

4.3.4 Agrobacterium-*Mediated Transformation*

Agrobacterium tumefaciens is a soil-inhabiting bacterium which has, during evolution, developed a natural ability to transfect plants. It mobilizes and integrates its tumor-inducing (Ti) plasmid into plant cells' nucleus (Chotani et al. 2000). This natural phenomenon can serve the purpose of transfecting plant cells with desired DNA material. *Agrobacterium* strains carrying no tumor-forming genes have already been developed by scientists. Gene of interest is first inserted in *Agrobacterium tumefaciens*' Ti plasmid; hence, it carries the targeted gene along with the transfer DNA (T-DNA) when it infects the plants. On co-culturing with the plant tissues, the T-DNA as well as the gene of interest gets incorporated into plant's genetic material. Selection of successful transformants is then done using selection medium (Singh et al. 2013).

Initially developed for dicots, the transformation system has been optimized for the monocots such as sugarcane as well (Arencibia et al. 1999; Enríquez-Obregón et al. 1998; Manickavasagam et al. 2004). This approach offers advantages like high efficiency, lower costs, simple methodology, and transformation of larger DNA fragments. Additionally, it also has an edge of less sugarcane host genome rearrangements (Manickavasagam et al. 2004). Further, as compared to other approaches of cane transformation, it offers stable expression, greater efficiency, and lower transgene silencing. These characteristics make it an ideal system to find applications in sugarcane transformation (Dai et al. 2001; Singh et al. 2013). The first attempt of the successful *Agrobacterium*-mediated transformation was reported by Arencibia et al. (1998). Manickavasagam et al. (2004) also used *Agrobacterium*-mediated transformation for developing the herbicide-resistant sugarcane, whereas Carmona et al. (2005) employed this method to enhance the sugar contents of sugarcane plants by transforming sucrose–sucrose fructosyltransferase gene.

One of the major issues related to this transformation method is the fact that this system is highly genotype dependent. Hence, genotype screening for the purpose, source tissue of explant, and *Agrobacterium* strain can all play vital role in deciding the success of *Agrobacterium*-mediated transformation (Arencibia et al. 1998; Manickavasagam et al. 2004). To overcome such glitches, selection markers have been developed. For sugarcane, neomycin phosphotransferase II (nptII) gene (which confers resistance to phytotoxic amino-glycoside antibiotics like geneticin and kanamycin) is extensively used in transforming the callus (Joyce et al. 2010; Scortecc et al. 2012; Zhangsun et al. 2007).

Improvements such as the development of selection system and co-cultivated medium have greatly improved this transformation system for sugarcane transgenesis (Joyce et al. 2010). Another optimization before proceeding for a particular *Agrobacterium* transformation is the establishment of inhibitory concentration of the selective agent, which is tissue and species dependent (Yu et al. 2003). Numerous strains of *Agrobacterium tumefaciens* have been used for sugarcane transformation including AGL1, AGL0, and EHA105. Vectors which have been successfully exploited for the purpose include pBract 302 (Reis et al. 2014), pAHC27, pEmuKN (Pillay 2013), pMLH7133 (Efendi and Matsuoka 2011), Pu912 (McQualter and Dookun-Saumtally 2007), and pWBvec10a (Ithape et al. 2017; Joyce et al. 2010).

In spite of some of the intrinsic challenges of sugarcane transformation through this approach, it is an extremely promising strategy because of its ability to transfer larger fragments of DNA and low copy number. With the optimization of in vitro and embryonic culture parameters and use of appropriate *Agrobacterium* strains, this approach can serve as an excellent system of transformation for sugarcane (Souza and Sluys 2014).

4.3.5 RNA Interference (RNAi)

RNAi is basically a mechanism of defense found in plants, animal, and microbes. This system is quite common and conserved in various species (Carthew 2001). A cellular enzyme called Dicer plays vital role in this defense system. It recognizes any double-stranded RNA (dsRNA) in the cytoplasm, binds to it, and digests such RNA into small interfering RNA (siRNA) duplexes. These siRNAs then function as sequence-specific tags in the cell (Zhang et al. 2013). Hence, introducing dsRNA in cells can effectively lead to target gene silencing (Carthew 2001).

Role of small RNAs has been studied in sugarcane, and it was noticed that the small RNAs of 18–25 nucleotides are up- or downregulated under various stress conditions the plant is exposed to. It suggested a role of such RNAs in stress response and adaptation (Sunkar and Zhu 2004). Patade and Suprasanna (2010) reported the role of microRNAs on subjecting sugarcane plants to higher NaCl concentrations and dehydration. When compared against the control, they observed that certain targeted microRNAs were more responsive to osmotic stress rather than the ionic abiotic stress, suggesting specific role to microRNAs in the cytoplasm (Suprasanna et al. 2011).

RNAi is one of the most widely used techniques to study gene knockouts, and for suppressing the expression of undesired characteristics in crops. This technique has already served in tweaking of sugarcane for commercial characteristics like cell wall manipulation for second-generation biofuel production, downregulation of cinnamyl alcohol dehydrogenase for glucose production, and cellulase pretreatment efficiency and inhibition of ADP-glucose pyrophosphorylase for engineering starch synthesis (Jung et al. 2013; Saathoff et al. 2011; Zale et al. 2016).

4.3.6 Genome Editing

Genome editing is a set of modern tools to bring about desired changes into subject organisms. The term refers to a cutting-edge group of techniques which has revolutionized the perception of transgenics for crop improvement. DNA is either inserted, modified, replaced, or deleted by using specific engineered nucleases in these approaches. Nucleases employed in such mechanisms form double-stranded DNA break at the targeted locations in the plant genome. Once a double-stranded break is created, the host defense systems try to repair the breakthrough homologous recombination (HR) or non-homologous end-joining (NHEJ), producing mutations at the targeted location. The genome editing has undergone various developments over time, equipping the scientists with simple tools which can be used to produce specific and controlled additions, deletions, or modifications into the host genome (Mohan 2016).

Major techniques of genome editing include meganucleases, zinc finger nucleases (ZFNs), transcription activator-like effector nucleases (TALENs), and the clustered regularly interspaced short palindromic repeats/CRISPR-associated (CRISPR/Cas) technology. In 2016, Jung and Altpeter (2016) employed the TALEN system for modifying cell wall traits of sugarcane. They targeted to produce sugarcane genotypes with lesser lignin content in the cell wall to enhance their digestibility for lignocellulosic ethanol production.

CRISPR/Cas is the latest and most prominent genome editing system which has revolutionized research in biological sciences because of its high efficiency, simplicity, and cost-effectiveness (Mohan 2016). It evolved in bacteria as an immune system to counteract vs. invading foreign nucleic acids. In CRISPR/Cas strategy, double-stranded DNA nuclease conducts RNA-based recognition of the target sequences (Puchta 2016). This system comprises of CRISPR RNA (crRNA) and the Cas proteins. The crRNA is complementary to target DNA; hence, it guides the Cas proteins for identifying and chopping the target sequence. Once cleaved, the DNA is repaired either through NHEJ or HJ. NHEJ gives rise to mutations in the target sequence, while HR produces precise and specific genomic variations (Haurwitz et al. 2010; Yao et al. 2018).

For genome editing of crops, a careful analysis of the target sequence is done and a synthetic-guide RNA (sgRNA) is designed complementary to the target DNA, which then directs the Cas nuclease to the target. The Cas complex is delivered along with the sgRNA into the cell, which subsequently deletes the existing genes, edits them, or adds new ones at the precise location (Haurwitz et al. 2010). This is an extremely efficient and useful system which has been greatly welcomed by the scientific community and molecular biologists.

Till date, numerous plant species, including sugarcane, have been engineered using this technique (Mohan 2016; Shih et al. 2016). sgRNA has a simple structure and therefore constructs can be easily be designed to deliver multiple sgRNAs simultaneously. CRISPR/Cas can create a high rate of mutagenesis at a precise location in the genome; moreover, multiple genes in a family or several genes involved in a metabolic pathway can be modulated (Ma et al. 2015; Shih et al. 2016; Zhou et al. 2014). Nevertheless, limited availability of functional genomics data for sugarcane present challenges which still need to be tackled before such techniques could find routine applications in this crop (Mohan 2016).

4.4 Possibilities to Explore for Enhancing Biofuels and Bioenergy Production from Sugarcane

Transgenic approaches can interplay with a huge number of factors associated with biofuel production in sugarcane. Breakthroughs can be made in making the second-generation ethanol production cost-competitive by developing cane lines having reduced lignin, high yield, better ratio of cellulose-to-noncellulose content, *in planta* enzymes, pest and disease resistance, flowering inhibition, enhanced sugar quantities, improved resilience to biotic and abiotic stresses, and other agronomic traits (Arruda 2012; Hoang et al. 2015; Matsuoka et al. 2009; Sticklen 2006; Waclawovsky et al. 2010). The following is a major list of possibilities which can be explored for realizing better, higher, and cost-effective biofuel production from sugarcane.

4.4.1 Transgenes for Enhanced Sucrose Accumulation

Sugar concentration, like every other biological pathway and phenomenon, is regulated by various control mechanisms. Such mechanisms put a barrier against genetic manipulations targeting elevation in sucrose levels, thus buffering against such changes (Capell and Christou 2004). Aforesaid regulatory systems may include specific sucrose sensors as well as broad osmotic feedback mechanisms; thermodynamic limitations, viz., leakage of sucrose from storage through membranes; or energetic mechanisms of synthesis and cleavage of sucrose (Bindon and Botha 2002; Wu and Birch 2007).

Bypassing cellular regulation and feedback limitations to alter the genetic architecture of the complex genome of sugarcane is an extremely arduous task. However, apprehending that all of such regulations are basically sucrose based, it has been speculated that expressing other forms of sugar instead of sucrose would bypass the source–sink boundaries. The newly introduced sugars can then contribute toward food as well as the biofuel sector. Isomaltose (IM) has been identified as a potential candidate to realize the said targets and overcome the aforementioned barriers.

IM has a growing market as a stable sugar which is digested slower as compared to sucrose. Additionally, IM is acariogenic and nonhygroscopic form of sugar (Lina et al. 2002). Characteristics of IM like gradual digestion and accessible carbonyl group make it an alluring target for expressing in sugarcane (Lichtenthaler and Peters 2004). Wu and Birch (2007) strived to introduce sucrose isomerase (SI) gene in vacuolar compartmentation, which significantly bolstered up the total sugar levels in cane. IM accretion did not impact the sucrose concentration, and hence resulted in doubled total sugar concentrations against the elite parent cultivar. IM level of 440 μ mol g^{-1} of fresh weight in sugarcane was observed (Wu and Birch 2007).

Alternatively, possible routes to enhance carbon fixation may include increasing sugar yields by improving photosynthetic capacity through cynobacterial heterologous RuBisCO, and tackling the photorespiration and Calvin–Benson cycle through metabolic engineering (Lin et al. 2014). Metabolic engineering for sink–side strategies for pulling a higher level of carbon by sugar biosynthesis into other products of interest is a promising strategy as, otherwise, sucrose accumulation hampers photosynthesis as a result of feedback controls. Developing a different sink or enhancing the carbon in the form of some other sugar will avert any such feedback mechanism against photosynthesis, resulting in auspicious outcomes (Shih et al. 2016).

4.4.2 Transgenesis for Second-Generation Ethanol Production: Lignin Biosynthesis Engineering

Sugar mills have traditionally been consuming bagasse for producing heat, which is used to run boilers. Later on, the practice of generating electricity was adopted by the sugar industry. However recently, it has been seen that the same can be employed for biofuel production as well (Pandey et al. 2000). Nevertheless, breaking the complex interlinkages of the cell wall (CW) components requires pretreatment and biologically derived cellulases, adding huge costs to the process. Therefore, second-generation biofuel production has remained noncompetitive and its commercialization has stayed stagnant (Halling and Simms-Borre 2008).

Pretreatment is required for removing the recalcitrant components before bagasse can be converted into bioethanol. Keeping the high costs of second-generation biofuel production in view, biotechnological approaches can find applications in improving sugarcane for increasing the yield of the second-generation biofuels and for making their production remunerative. Producing higher biomass, enhancing fiber contents, and augmenting biodegradability of the CW are some of the promising targets in this regard (Hoang et al. 2015).

While sucrose-derived biofuel production system based on using sugarcane as feedstock has already been commercialized successfully in Brazil, sugarcane also yields huge quantities of lignocellulosic residues in the form of tops, leaves, and bagasse responsible for around 55% the aboveground biomass of cane plant (Somerville et al. 2010; Tew and Cobill 2008). Employing both the sucrose and lignocellulosic fractions for biofuel production can double the ethanol yields per unit area of cultivation (Goldemberg 2007). The crop retains a substantial amount of sugars in its CW. These sugars are present in the form of polysaccharides such as cellulose, hemicelluloses, and pectin. Howbeit, such components of CW are strongly cross-linked with lignin, impeding the reachability of enzymes involved in fermentation process and hindering the degradation of CW polysaccharides to simpler sugars—which could later be converted into fuel ethanol. Large energy input is needed for digesting the CW, thus making the process exorbitant (Ndimande 2014).

For second-generation biofuel production from sugarcane, the structure of fiber fraction of the crop plays a decisive role. The chief structural component of the fiber part is cellulose, which accounts for approximately 50% of the dry weight (DW) of sugarcane bagasse. Hemicellulose is formed of noncellulosic polysaccharide components and shares 25% of the bagasse DW, whereas 25% is contributed by lignin fraction (Hoang et al. 2015; Loureiro et al. 2011; Mutwil et al. 2008; Pauly et al. 2013). The fiber part of the sugarcane is designed to serve as a skeleton to support the plant. The cellulose and hemicellulose fractions strengthen the fiber component and are reinforced by lignin and phenolic cross-linkages. The interweaving of elements of CW provides defense to sugarcane; however, as evident, this also introduces new challenges regarding biofuel production, necessitating pretreatment steps for dissolving the CW (Hoang et al. 2015).

Lignocellulosic biomass represents a renewable and noncompeting source of ethanol, which possesses high carbon balance. The second-generation biofuels do not hamper food production, which is one of the greatest concerns against biofuels. Moreover, lignocellulosic biomass is an abundantly available renewable alternative. Additionally, this promising source of biofuels is more competitive in terms of net energy and CO_2 balance (Hoang et al. 2015). Yet, the costs of cellulase enzymes and the pretreatment process are too high. Efforts have therefore been made to reduce these expenses through genetic engineering. Lignin modification is anticipated to be a promising path to resolving this hitch, whereas other stratagems enlist as augmenting plant polysaccharide contents and increasing the biomass (Sticklen 2008).

Lignin biosynthesis is extremely intricate as there are around 10 enzymes involved in lignin synthesis (Whetten and Sederoff 1995), whereas 28 unigenes are reported to be linked with monolignol biosynthesis (Bottcher et al. 2013). Tailoring of the sugarcane CW composition can be attempted by manipulating key genes involved in the lignin biosynthesis. Suppressing or limiting the expression of genetic role players is expected to abate the lignin content in CW. The terminal enzymes such as caffeic acid O-methyltransferase (COMT) and cinnamyl alcohol dehydrogenase (CAD) are exceptional targets in this regard as modulating them is not likely to affect the growth and development of the plant in general (Hoang et al. 2015; Jung et al. 2012; Sticklen 2006).

Apart from huge costs of the conventional digestion process, another associated complexity of traditional approaches is the fact that they can negatively impact the ultimate ethanol engenderment by degrading sugars and adding inhibitory molecules (Alvira et al. 2010). Hence, lignin engineering, through molecular tactics, is an attractive target for second-generation biofuel production.

Lignin is constituted by polymerization of three components, viz. monolignols, including p-coumaryl, coniferyl, and sinapyl alcohol, which are termed as p-hydroxyphenyl (H), guaiacyl (G), and syringyl (S) units, respectively, after incorporation of these monolignols into the lignin polymer (Bonawitz and Chapple 2010). Grabber (2005) reported that lignin also contains hydroxycinnamic acids including p-coumarate and ferulate as structural constituents. The role of ferulate has been designated as interlocking of the hemicellulosic CW with the lignin and polysaccharides (Grabber 2005), while p-coumarate, which is known to be esterified to sinapyl alcohol, is involved in increasing the integration of this monolignol in the lignin polymer (Hatfield et al. 2008; Ralph et al. 1994).

COMT is an exceptional target for modulating the monolignol biosynthesis. This enzyme conducts the production of sinapaldehyde and sinapyl alcohol through O-methylation at C5 position of 5-hydroxyconiferaldehyde and 5-hydroxyconiferyl alcohol, respectively (Louie et al. 2010). COMT suppression in mutants or transgenically engineered plants reduces lignin content, highlighting its role in sinapyl alcohol biosynthesis (Fu et al. 2011; Palmer et al. 2008). Hence, downregulation of lignin biosynthetic gene(s) is a felicitous strategy to enrich saccharification efficacies and enhance lignocellulosic ethanol outturns (Chen and Dixon 2007). Fu et al. (2011) used this approach for genetic manipulation of switchgrass and reported a consequent rise in ethanol production. Saathoff et al. (2011) also proposed that employing RNA interference (RNAi) for downregulation of cinnamyl-alcohol dehydrogenase can enhance the glucose production and cellulase pretreatment efficiency in switchgrass.

Similarly, Jung et al. (2012) exploited RNAi to suppress the COMT gene in sugarcane. The downregulation was observed to be as high as 67–97%, indicating the efficacy of this strategy. Plants were seen to have a decline in lignin content by 3.9–13.7%. Moreover, the syringyl/guaiacyl ratio curtailed to 1.27 and 0.79 against 4.47 in the wild type (WT) sugarcane. The transgenic lines demonstrated total lignin content of as low as 156.6 vs. 181.4 mg g^{-1} of the WT plants. Overall, a moderate reduction of up to 8.4% was suggested to limit the recalcitrance of cane biomass without trading off the plant performance. The yield of directly fermentable glucose from the lignocellulosic biomass was augmented by 29% barring any pretreatment, while a pretreatment step of dilute acid was observed to enhance the glucose yields up to 34% (Jung et al. 2012).

In a follow-up study, scientists evaluated the field performance of COMT-suppressed transgenic lines in the United States (Jung et al. 2013). GM lines showed up to 12% decline in lignin content as compared to WT, whereas the S subunit content was abridged by up to 49% in some plants (Jung et al. 2013). Moreover, transcript reduction of up to 91% was obtained, indicating successful suppression of the targeted gene. Reducing the lignin by 6% did not adversely impact the biomass yield and other agronomic characters, brix values, or total structural carbohydrates of the crop, while, as a significant outcome, the saccharification efficiency ameliorated by 19–23%. It was estimated that the hydrolysis of transgenic lines could be carried out in one-third of the hydrolysis time required otherwise, employing 3–4 folds less enzymes for yielding equal amount fermentable sugar than the WT plants (Jung et al. 2013).

Jung and Altpeter (2016) have exploited TALEN-mediated mutagenesis to create variations in the genomic region of COMT. They observed mutations in around 74% of the lines subjected to genome editing, whereas 8–99% of the WT COMT were seen to have converted into mutant COMT in different plants. Mutations in COMT correlated with the lignin biosynthesis, resulting in 29–32% decline in lignin against WT parent. Interestingly, this was the first report of genome editing of sugarcane, as per our knowledge, indicating the importance and interests in improvement of second-generation cane biofuel production phenomenon (Jung and Altpeter 2016).

Another possibility is to play with the lignin-composing units, as a better-degrading type contains virtually exclusively of syringyl in lieu of recalcitrant guaiacyl lignin (Papes et al. 2015). The variations in guaiacyl and syringyl levels are not significantly treacherous. Shifts in guaiacyl and syringyl levels generally have only minor effects on the plant development (Vanholme et al. 2010). CW lignin resulting from such structural alterations developed though GM strategies can be much more easily processed, facilitating the second-generation ethanol production (Maldonado et al. 2010).

4.4.3 Mix-Stock Concept Through GM Techniques: Sugarcane as Enzyme Factory

Immoderate production cost is one of the greatest impediments against commercial scale expansion of second-generation ethanol (Harris and DeBolt 2010; Margeot et al. 2009). Bagasse, one of the most widely available lignocellulosic materials available in tropics and subtropics, can be efficiently utilized only once the second-generation ethanol production becomes economically feasible. It is evident that the competitiveness of lignocellulosic ethanol production largely depends on cane biotechnology breakthroughs (Yuan et al. 2008).

Digesting “from within” is a recent concept being exploited by sugarcane researchers. This strategy can simplify or even omit the requirement for pretreatment. In this approach, cellulolytic and hemicellulolytic enzymes are produced in the sugarcane itself (Fan and Yuan 2010; Ferreira-Leitão et al. 2010). Degradation of lignocellulosic biomass needs approximately ten enzymes and those too in huge quantities of approximately 15–25 kg cellulase per ton of biomass (Carroll and Somerville 2009; Fan and Yuan 2010). These enzymes are extremely expensive as they are obtained from microbiological sources. Therefore, a new concept developing in this context is to produce the enzymes needed for hydrolysis within sugarcane itself using genetic engineering.

Using *Agrobacterium*-mediated transformation, exogenous enzymes can be expressed in leaves and other tissues of sugarcane (Manickavasagam et al. 2004). Harrison et al. (2011) reported the accumulation of cellobiohydrolase and endoglucanase in leaves of transgenic sugarcane. Three different cellulolytic enzymes including fungal cellobiohydrolase I (CBH I), CBH II, and bacterial endoglucanase (EG) were expressed simultaneously using PepC promoter from maize. Up to 0.05% (of the total soluble proteins) accretion of endo- and exoglucanases was seen to have no negative impact on plant health (Harrison et al. 2011). These results depicted an optimistic future for the cost-effective production of lignocellulosic ethanol from sugarcane.

In planta enzymes are expected to be more efficient, and the need for harsh and expensive pretreatment is anticipated to descend, although thermal stability of such enzymes is a challenge since they are eventually to be used in harsh processing conditions of bioreactors (Sanchez et al. 2010). Nevertheless, avenues of *in planta* enzymes’ production are not undemanding. Inducible promoters are necessary for expressing any such cellulase so that the enzymatic activity starts only before harvest—or else it would damage the plant growth and development. Knowledge regarding such details is limited, hindering the applications in genetic engineering and pointing toward considerable room for improvement hitherto (Dale 2007; Harris and DeBolt 2010; Maldonado et al. 2010).

4.4.4 GM Sugarcane for Diesel Production

Storage lipids of plants, majorly constituted by glycerol esters of fatty acids—also termed as triacylglycerols (TAGs)—are among the energy-rich forms of reduced carbon (Durrett et al. 2008). TAGs have huge energy contents, greater than twice of the carbohydrates. Hence, TAGs can also be exploited for bioenergy production. They can be converted into biodiesel by changing their acyl chains to fatty acid methyl esters (Ohlrogge and Chapman 2011). Additionally, abundant availability of TAGs also makes them an advantageous target for bioenergy engenderment.

Traditionally, oil seed crops have been used for biodiesel production as seeds or fruits of such crops contain high amounts of TAGs. However, their use in bioenergy production at large scale is not viable as expanding their production solely for this purpose may overshadow food production. Moreover, employing seeds in the energy sector would increase food prices, introducing a question mark on the sustainability of any such system (Ohlrogge and Chapman 2011). Recent approach to biodiesel production, i.e., enhancing lipid content in the vegetative tissues of plants rather than seeds, has opened a new paradigm to develop sustainable biodiesel production options (Chapman et al. 2013). Being a great producer of biomass, sugarcane has been considered as a potential candidate for biodiesel engenderment as well. As a C4 plant and an extremely efficient photosynthesizer, its potential for biodiesel production, like bioethanol and bioelectricity, is huge (Tew and Cobill 2008).

Metabolic engineering of sugarcane, apart from producing promising results in second-generation ethanol production, is also paving its ways toward exploring the possibility of biodiesel production from this feedstock. Therefore, current strategies are targeting to reroute the carbon flux to upregulate the lipid biosynthesis (Vanhercke et al. 2014; Zale et al. 2016). TAGs are being attempted to be produced in vegetative tissues of the plants, and promising results have already been observed in model plants like *Arabidopsis* and tobacco (Chapman et al. 2013; Petrie et al. 2012). In Tobacco, accretion of 19% of TAGs by DW have been obtained using genetic engineering through expression of three genes, namely, WRINKLED1, DGAT, and Oleosins (Vanhercke et al. 2014; Zale et al. 2016).

Recently, similar efforts have been attempted on sugarcane as well. Three lipid-producing genes have been expressed in engineered sugarcane, resulting in an accumulation of 5% TAGs and 10% total fatty acids (Huang et al. 2015; Zale et al. 2016). Field trials of lipid cane are also in progress, and a target of around 20% lipid concentration with respect to DW is being strived for. At this concentration of lipids in cane, the cost of biodiesel will be \$0.59 L^{-1} which would be significantly lower than the cost of biodiesel production from soybean at \$1.08 L^{-1}. Moreover, since sugarcane has higher productivity, 6700 L of biodiesel can be produced per hectare against just 500 L from soybean (Huang et al. 2016).

Multigene metabolic engineering has been successfully done, yielding promising results. WRINKLED1 (involved in TAGs accumulation), diacylglycerol acyltransferase 1–2 (catalyzes the conversion of diacylglycerol to TAGs), and oleosin1 (reduces lipid turnover) were expressed, coupled with RNAi-mediated inhibition of ADP-glucose pyrophosphorylase (part of starch biosynthesis) and peroxisomal fatty acid ABC transporter (conducts lipid transport for b-oxidation) in a remarkable study by Zale et al. (2016). An accumulation of 1.9% TAGs of DW of sugarcane leaves was recorded, which is 95-fold higher than the WT sugarcane (0.02% only in WT). Moreover, accumulation in the stem was observed to be around 0.86% against 0.02% of WT. As sugarcane is a huge biomass producer, mainly contributed by its stem, deputing a strong stem-specific promoter for the purpose could enhance TAGs yields of the plant even more (Zale et al. 2016).

Zale et al. (2016) also reported that up to 4.6% fatty acids of the DW were agglomerated in sugarcane; this amount was as high as threefold than the WT cane. It has also been suggested that every single percent rise in TAGs accumulation in cane corresponds to total oil yield from the same area of canola. Stacking of additional genes and further optimization of expression cassettes are anticipated to produce even higher lipid yields from sugarcane, making it a sustainable biodiesel producer.

4.4.5 Biomass Improvement

Nearly 600 million tons of sugarcane dry lignocellulosic biomass is available worldwide, and per hectare yield of lignocellulosic biomass is around 22.9 dry tons per year (Van der Weijde et al. 2013). Bioethanol yield of the cane bagasse only is 3000 L ha^{-1}. Whereas using both the sugar and bagasse 9950 L ha^{-1} of ethanol can be obtained (Hoang et al. 2015; Somerville et al. 2010). Therefore, increasing biomass yield of sugarcane would also enhance the quantities of ethanol from the same area of cane cultivation.

Garcia Tavares et al. (2018) exploited the hormonal regulation of culm development for increasing sugarcane biomass. They hypothesized that variation in expression of DELLA—involved in the regulation of plant growth promoting hormones like gibberellins—will play a crucial role in the growth and composition of cane culm. They modulated the ScGAI expression in sugarcane, and suggested that such changes led to differences in culm development. The ScGAI-silenced plants showed better height and internode length and higher carbon allocation to stem (Garcia Tavares et al. 2018). Hence, increasing the biomass potential is another promising strategy for producing higher amounts of second-generation biofuels from sugarcane.

4.4.6 Cellulose Accumulation

Enhancing the cellulosic and hemicellulosic fractions in sugarcane CW can increase the fermentable sugar contents of the crop, which would ultimately improve the second-generation ethanol yields. Hence, heterologously augmenting the expression of genes involved in the biosynthesis of cellulosic, hemicellulosic, and starch-like polysaccharides is another potential target for sugarcane transgenics in reference to ethanol production.

Transgenic lines were recently produced by Ndimande (2014) at Stellenbosch University. These lines expressed CsCesA gene, which encodes a cellulose synthase from the marine invertebrate *Ciona savignyi*. Transgenic plants showed higher activity of cellulose synthase enzyme, whereas cellulose contents were also enhanced. Expressing the said gene not only augmented the cellulose content in internodal tissues, but hemicellulosic glucose content and uronic acid were also observed to rise, while a decline in lignin was observed. Investigating the glucose release from transgenic lines, the superiority of such plants was recorded over the WT plants (Ndimande 2014).

4.4.7 Transgenic Energy Cane

Energy cane has recently been developed by the Department of Energy (DOE) in the United States, and it has been identified as a potential lignocellulosic feedstock because of its huge biomass yields and strong resilience against biotic and abiotic factors, enabling it to grow on low-value lands with fewer inputs. Since developments in sugarcane transgenics are already paving their way, high lignocellulosic biomass of energy cane is also important in this regard. Once improved and cost-effective cane energy conversion techniques are developed, the huge biomass of energy cane can be used efficiently for bioethanol as well as bioelectricity production (Tew and Cobill 2008).

As a start toward energy cane transgenics, an efficient biolistic gene delivery protocol has been developed. Expression cassette of P-ubi::nptII::35S polyA derived from plasmid pJFNPTII was used in these studies, and successful transformation as well as plantlets' growth was observed through tissue culture. The study indicated that energy cane, which already possesses many of the parameters of interest, can be genetically manipulated to return even higher benefits (Fouad et al. 2015).

4.4.8 Biotic and Abiotic Stress Tolerance

Apart from factors which directly influence bioethanol yield and the competitiveness of its production process, various components involved in crop production costs, stress tolerance, and agronomic improvement can also be optimized through transgenesis. Sugarcane transformation and genome editing can substantially serve in enhancing the biotic and abiotic stress tolerance of the crop, which can upsurge the sugarcane's role as a biofuel producer. Such approaches have been extensively exploited for a while, resulting in promising outcomes.

Water, being one of the major inputs of sugarcane and main concern against large-scale sugarcane production, is a crucial limiting factor in many regions of the world. Water-intensive crops are discouraged in various areas because of unavailability of excessive water resources to meet the crop needs (Maldonado et al. 2010). Water deficiency seriously jeopardizes sugarcane growth, and it can cause up to 50% yield losses (Inman-Bamber 2004).

Trehalose is known to be involved in protecting cellular structures from dehydration (de Jesus Pereira et al. 2003). Therefore, genes associated with trehalose have been utilized in GM sugarcane for enhancing water stress tolerance. The transgenic sugarcane not only grew better, but it also showed higher resilience against water deficiency, recovered faster against this stress, and produced higher contents of sugar (Zhang et al. 2006). Likewise, Reis et al. (2014) employed the stress-inducible overexpression of AtDREB2A CA for boosting cane tolerance against water stress. The transgenic plants were seen to have higher level of sucrose, better bud sprouting, and improved relative water content vs. the control plants (Reis et al.

2014). Moreover, Saravanan et al. (2018) expressed BcZAT12 gene isolated from *Brassica carinata* in sugarcane for increasing its salt and drought tolerance, whereas Kumar et al. (2014a) induced salinity stress tolerance in sugarcane employing *Arabidopsis* vacuolar pyrophosphatase (AVP1) gene. Further, GM-based expression of Δ1-pyrroline-5-carboxylate synthetase (P5CS) gene has also shown higher salinity tolerance in cane (Guerzoni et al. 2014).

Sugarcane transformation has also been exploited for developing resistance against biotic stresses. Genetic manipulation has been used as back as in 1997 for developing resistance against the yellow leaf virus (Arencibia et al. 1997, 1998, 1999). Furthermore, herbicide-resistant sugarcane has also been developed using *Agrobacterium* strains LBA4404 and EHA105 carrying neomycin phosphotransferase II, phosphinothricin acetyltransferase (bar), and gus-intron genes (Manickavasagam et al. 2004). The transformed crop did not show herbicide's issue when sprayed with BASTA (glufosinate), and thus, it could significantly facilitate the management practices and reduce crop production costs (Manickavasagam et al. 2004).

For commercial applications, Monsanto is using well-known Bt technology for incorporating resistance in sugarcane against pests and insects (Maldonado et al. 2010). Sugarcane production is expected to be exceedingly profitable as GM technologies decrease its production costs and increase its resilience against biotic and abiotic stresses.

4.5 Success Stories

Transgenic sugarcane lines have been produced in many countries of the world, and the results have been very encouraging. So far, the sugarcane transgenics have been produced for higher sucrose and biomass yield (Botha and Groenewald 2001), abiotic stress tolerance (Raza et al. 2016), herbicide tolerance (Gallo-Meagher and Irvine 1996), pest resistance (Arencibia et al. 1999), downregulation of lignin production for making second-generation ethanol production cost-effective, and expression and accretion of microbial cellulosic enzymes in sugarcane tissues realizing mix-stock concept (Harrison et al. 2011), among others. Biotechnological efforts are also underway for enhancing the nutrient use efficiency of sugarcane. Nitrogen use efficiency is one of the major targets of such efforts in order to grow sugarcane in nitrogen-poor conditions (Maldonado et al. 2010).

Successful expression of additional forms of sugar has opened new avenues of research for bypassing the sucrose regulation barriers and breaching the sucrose ceiling in sugarcane (Birch 2007; Wu and Birch 2007). Such accomplishments can significantly supplement the first-generation route of ethanol production from sugarcane. Sugarcane lines producing additional forms of sugar, apart from sucrose, are in field trials in Australia (Maldonado et al. 2010).

Accomplishing the use of sugarcane as an enzyme factory is another tremendous achievement. Cocktails of several enzymes have been expressed in sugarcane. Such developments, when used commercially, will considerably reduce the costs related to engenderment of second-generation biofuels. Cost of production for these enzymes in plants is like 1000–3000-fold lower than the expenses when they are purchased commercially. Additionally, *in planta* enzymes are far more efficient as well (Verma et al. 2010). Field trials are underway for sugarcane cultivars expressing lignocellulolytic enzymes (Ewing 2008; Maldonado et al. 2010). Furthermore, biodiesel production from transgenic sugarcane is another landmark discovery which can transform the role of sugarcane in world's energy matrix in future (Huang et al. 2016).

The National Genetically Modified Product Biosafety Commission (KKHPRG) of Indonesia approved GM sugarcane modulated for having drought-tolerance in 2013 (International Service for Acquisition of Agri-Biotech Applications 2013). In Brazil, the first GM sugarcane was approved for commercial release in 2017. Approved variety called CTC 20 Bt has resistance against sugarcane borer, the major plague of sugarcane crop which causes huge losses to the crop every year and adds significant costs to sugarcane production. This variety was developed by CTC Centro de Tecnologia Canavieira Sa, which proposed that the Bt gene and its protein are entirely eliminated in the sugarcane derivates during fabrication. They also proposed that no harms on soil composition, biodegradability, and insect populations were observed cultivating this GM cane (AgroNews 2017). Drug and Food Regulatory Authority in the United States approved the sugar produced from GM sugarcane in 2018, calling it safe for consumption (Preto 2018).

4.6 Challenges

Transgenic sugarcane production, in spite of being widely explored, faces several challenges. GM sugarcane production is exceptionally complicated because of the complex polyploidy of sugarcane which deters the application of several tools employed in other species (Birch 2007). The genome of commercial sugarcane is contributed approximately 80–90% by *S. officinarum* and 10–20% by *S. spontaneum*. High level of recombination and heterozygosity complicates transgenic attempts for sugarcane as its genome can have 10–14 copies of each chromosome (Henry and Kole 2010).

Moreover, genome editing tools like CRISPR/Cas make use of transformation methods such as protoplast transfection, generation of stable transgenics, and agro-infiltration. For sugarcane, transient methods like agro-infiltration and protoplast fusion have a low success rate. *Agrobacterium*-mediated sugarcane transformation is quite well established and a widely used approach in sugarcane transgenics. However, it is laborious and time-consuming technique of transgenesis having low efficiency (Joyce et al. 2010).

Unavailability of functional genomics data is another limitation against genome editing of sugarcane. For instance, apposite designing of sgRNA is the very first step in CRISPR/Cas. Therefore, it is a prerequisite to be aware of the allelic variations in the target crop. Functions of a huge number of sugarcane genes are still unknown, and only a few transcriptomic data sources are available for sugarcane, making the application of simple genome editing approaches like CRISPR/Cas difficult (Mohan 2016).

Transgene silencing is another problem to be addressed in sugarcane transgenics, as sugarcane has high efficiency to silence transgenes. Sugarcane does transcriptional as well as posttranscriptional gene silencing of transgenes (Hansom et al. 1999; Mohan 2016). However, it has been seen that such gene silencing is promoter-cassette dependent, indicating that the silencing can be tackled by using more efficient and suitable constitutive promoters (Birch 2007; Pillay 2013; Singh et al. 2013).

Furthermore, sugarcane is a perennial crop taking 12–18 months to reach maturity. Hence, a longer growth period would be required for developing and evaluating sugarcane transgenics. A further issue regarding sugarcane transgenics is the GM distinction, viz., differentiating the GM from non-GM may not be possible in the long run. It may become difficult to recognize whether a line is a product of nature or a result of earlier genetic manipulation, which increases concerns against transgenics.

Another hurdle regarding sugarcane transgenics is the "approval and acceptance." Regulatory requirements are strict about the approval of transgenic crops, and such reservations even increase if the crop products are to be used as food. Hence, sugarcane is subject to strict government regulations considering GM concerns for approval in many of the countries. Although Brazil and Indonesia have already approved GM cane, endorsement may take a while in other cane-growing countries. Even after approval, acceptance by the society and stakeholders is another substantial concern in this reference.

4.7 Future Prospects

Sugarcane has significant advantages over any other energy crop. It has C4 photosynthetic system which enables it to photosynthesize very efficiently, converting sunlight into chemical energy. Moreover, it has substantially higher per hectare yield compared to any other crop (Khan et al. 2017c). Apart from bioethanol and bioelectricity, sugarcane transgenesis has added another energy product in the list, i.e., biodiesel after success of efforts for producing higher concentrations of TAGs in the crop (Zale et al. 2016). Lipid production in sugarcane is expected to rise in coming years as it can produce far higher quantities of biodiesel per unit area of the crop cultivation. For instance, the United States harvests up to 220 MT ha^{-1} of cane, whereas the yield of soybean, another crop used for lipid production, is only 2.8 MT ha^{-1}. An additional advantage is the fact that sugarcane farming can still be enhanced in certain countries (e.g., countries in Africa) where suitable underutilized land is available (de Oliveira et al. 2006; Huang et al. 2016).

GM sugarcane has also been equipped with improved CW structural changes which can make the digestion of lignocellulosic materials simpler and economic.

Even more, expression of cellulases in sugarcane itself has also opened new horizons to make the second-generation fuel engenderment feasible and cost-effective. Hence, GM sugarcane can be anticipated to play a crucial part in biofuel and bioenergy production in coming years (Huang et al. 2016). Economically, sugarcane has a well-established industry in several cane growing states; it can generate energy for running boilers of the mills; it has low GHG emissions; and it has several socioeconomic advantages for people living in the vicinity of the sugar industry (Wang et al. 2012).

Harvesting this single crop can yield sugar for world's requirements, produce bioethanol to be used as vehicle fuel, yield electrical energy for export to the national grid, and engender biodiesel for running heavy automobiles, simultaneously. All of this will be possible once sugarcane transgenics are launched and used commercially. Even more, sugarcane, as a biorefinery, can produce a huge number of inputs for other industries including paper industry, hard boards production, and medical and liquor industry.

Sugarcane transgenesis is expected to become simpler and less laborious in recent future. Its huge genome has eventually been sequenced last year (Garsmeur et al. 2018). Furthermore, intense efforts are underway regarding transcript profiling, and some of such attempts have already been completed, giving insights into candidate role players in sugar and fiber production and their accumulation in the cane (Hoang et al. 2017). Additionally, several efficient sugarcane promoters have been identified and tissue-specific expression data have been made available in recent years (Souza and Sluys 2014). This kind of data can change the prospects of sugarcane transgenesis, making such endeavors straightforward.

Another fact which will contribute to the success of transgenic sugarcane production is the decreasing costs of sequencing through next-generation sequencing (NGS) technologies. NGS has made sequencing analysis extremely economic, simple, and rapid, which will facilitate the advances in functional genomics, transgene analysis, and genome editing (Goodwin et al. 2016; McCombie et al. 2018). Most importantly, as the new genome editing technologies like CRISPR/Cas mature, sugarcane genome editing will become a routine practice in molecular biology labs (Mohan 2016). It may soon be possible to replace sugarcane's endogenous inferior genes with the superior ones rather than transferring them from exogenous sources.

Social and regulatory acceptance for GM crops is developing with the passage of time. Approval of GM cane in Indonesia and Brazil is a landmark event in this regard, which will increase the confidence about acceptance of GM sugarcane (International Service for Acquisition of Agri-Biotech Applications 2013; Reuters 2017). Genetically manipulated sugarcane is also under field trials in Australia, Pakistan, and other cane-growing countries. Rigorous efforts by the biological sciences' experts and Nobel Laureates for developing consensus about safety of GM crops are anticipated to play vital role in public acceptance. Therefore, keeping in view the current scenario, benefits, and advantages associated with GM sugarcane for food, energy, and fuel production, it is expected that sugarcane transgenics will be widely adopted by the industry to harvest maximum benefits from this incredible crop.

4.8 Conclusion

GM sugarcane can play a paramount role in world's energy matrix as an energy source. Genetic manipulation of sugarcane can enhance its resilience for biotic and abiotic stresses, make second-generation ethanol production feasible and can even introduce sugarcane as a source of TAGs—for ultimate biodiesel engenderment. Cost of sugarcane and cane-derived ethanol and biodiesel production can be dramatically reduced using genetic manipulation. Lignin reduction in sugarcane cell wall and accumulation of lignocellulolytic enzymes inside the crop itself will persuasively upsurge sugarcane bioethanol production. Moreover, biodiesel production from sugarcane is also extremely feasible because of its huge yields per unit area; however, further rise in TAGs content is needed. Recent approval of GM cane in Indonesia and Brazil has augmented the prospects of GM cane's role in biofuel and bioenergy production.

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Part II
Sugarcane Biofuels Production in the World

Chapter 5
Biofuel Production from Sugarcane in Brazil

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5.1 Introduction

Biofuels, such as bioethanol, refer to the fuels produced from biological sources, e.g., sugarcane, corn, and wheat (Antunes et al. 2014; Balat and Balat 2009; Canilha et al. 2012; Hamelinck et al. 2005). Biofuels can be classified into first- or second-generation, according to the raw material they are extracted from. Bioethanol is a high-octane number fuel having excellent oxygen content, which makes it a promising alternative and additive for gasoline, facilitating cleaner combustion by increasing the oxygen content of the fuel (Goldemberg et al. 2008). First-generation bioethanol is produced on a large scale usually from sugarcane, sugar beet, and corn (Brennan and Owende 2010; Khan et al. 2017), presenting established technology with viable and consolidated economic levels. Second-generation bioethanol (2G), on the other hand, is produced from lignocellulosic biomass, such as agricultural and forest residues (e.g., sugarcane bagasse and wheat straw) (Aditiya et al. 2016). Its large-scale production is yet in development, with many bottlenecks to overcome regarding its economic viability.

Brazil is the biggest sugarcane producer in the world (Canilha et al. 2012), producing around 650 million tons of sugarcane in 2017 (National Supply Company [CONAB] 2017). This biomass has a great sucrose content, adequate for bioethanol production. (Canilha et al. 2012). However, after extraction of sugarcane juice for subsequent ethanol or sugar production, the residual sugarcane bagasse is generated

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in a ratio of 140 kg of bagasse per ton of processed sugarcane that it is usually burnt. However, keeping in view to its composition, a better valuable use can be taken into account (Canilha et al. 2010). Bagasse is mainly composed of cellulose (45%), hemicellulose (24%), and lignin (23%) (Rodrigues et al. 2010). Cellulose and hemicellulose are rich in fermentable sugars that can be released from sugarcane bagasse structure through a pre-treatment step and used as carbon source for ethanol production (Canilha et al. 2012; Gírio et al. 2010). The breakdown of hemicellulose fraction releases mainly xylose, requiring a microorganism that could assimilate this carbohydrate. However, this still is a challenge due to low availability of efficient microorganisms to assimilate C5 sugars (Canilha et al. 2012; Carvalho et al. 2013).

In recent years, new technologies for 2G bioethanol production have gained attention of scientific community aiming an economically competitive production process. However, it is an extremely complex process involving microbial fermentation, biomass pre-treatment, hydrolysate detoxification, and enzymatic hydrolysis (Naik et al. 2010; Nigam and Singh 2011). Establishment of an integrated production between first- and second-generation ethanol with value-added coproducts is an alternative to increase viability and improve the financial performance of the plant, creating the concept of biorefinery (Naik et al. 2010). The benefits of an integrated biorefinery are numerous due to the diversification of raw materials and products. Thus, the greater the degree of integration, the more economical, environmentally viable, and sustainable will be the process (Demirbas 2009).

Bioethanol from sugarcane has many advantages compared to fossil fuels and is an important alternative in the search of sustainable energies. Taking this into account, the acceptance, marketing, and evolution of ethanol in Brazil, as well as the current status of established 1G and 2G bioethanol trends, will be presented in this chapter.

5.2 Sugarcane in Brazil

5.2.1 Status of the Sugarcane Crop

The sugarcane crop was introduced in Brazil by Portugal as a strategy for colony's territory occupation. Portuguese government had already tested this model in Madeira Island, in which sugar production gave sufficient resources for maintenance of the colony. Brazil had perfect conditions for sugarcane's growth and development. In 1532, Mr. Martin Afonso de Souza officially introduced sugarcane at São Vicente's Captaincy, where currently São Paulo State is located, and built first Brazilian sugar mill. The crop was extremely important for Brazilian coast colonization, especially on northeast region at Bahia and Pernambuco States. Until the seventeenth century, sugarcane cultivation, for sugar production, had boundless expansion. This newly discovered gold became the greatest revenue from the colony, at that time. In the eighteenth century, France and England were the biggest producers of sugar, having the best technology of the sector, sharing the global market with the Netherlands and Portugal. The production growth in the Caribbean and Netherlands Antilles in the eighteenth century and the start of the use of sugar beets in Europe for sugar production, becoming self-independent at the beginning of the nineteenth century, weakened the Brazilian leading position in the world's sugar market. This scenario contributed for the nongrowth of Brazilian sugarcane until the beginning of the twentieth century.

The first half of the twentieth century was crucial for the national sugar sector. European sugar industry demolished due to World Wars, and the necessity to diversify São Paulo State's agriculture from coffee at the same time boosted sugarcane sector. In 1933 Alcohol and Sugar Institute (IAA) was created in order to regulate and modernize sugarcane production within the country. Development of new varieties resistant to pest and water deficiency started in 1926 by Agronomic Institute of Campinas, São Paulo (SP), and then also by IAA. Further, during the Second War, São Paulo increased its production in order to supply southern region of the country, thus becoming greatest Brazilian producer.

In 1969, one of the most active organizations regarding Brazilian sugarcane industry was established, called the Sugarcane Technology Center (CTC). CTC has been responsible for developing innumerable varieties of sugarcane through traditional breeding. Moreover, CTC, along with other counterparts, also released world's first genetically modified sugarcane in 2017. In 1975, during oil crisis, Brazilian government created the National Alcohol Program (*ProAlcool*) to take the country out of traditional gasoline dependence and bolster the sugarcane sector. In addition to the incentives for sugarcane sector, automobile industry also invested in production of vehicles fueled by ethanol, strengthening the domestic economy (Coelho et al. 2006; Pazuch et al. 2017).

From the beginning, sugarcane crop has been extremely important for Brazil's economy. Brazil is the major producer of sugarcane in the world, followed by India, China, and Thailand, according to Food and Agriculture Organization of United Nations (FAO 2017). Various factors, such as land availability, suitable climate, and desirable soil profile, support sugarcane production in the country. In addition to natural aspects, the sugarcane sector as a whole is supported by research, incentive programs, and government founding (Brazilian National Water Agency 2017; Martinelli et al. 2011; Scheiterle et al. 2017).

The crop production for 2017/18 is estimated to be 647.6 million tons, cultivated at 8838.5 thousand ha. This area is 2.3% smaller than the area cultivated last season (Fig. 5.1). Sugar worth instability, less competitive ethanol price against gasoline in internal market, and dry seasons during last few years are some reasons for this decline. Historically, the major sugarcane production and harvested area is from São Paulo state, which encompass 35,2214.0 thousand tons of cane production on an area of 4558.4 thousand ha expected for 2017/18. Unlike overall production, higher productivity was expected in Brazil for the same period (73,273 kg ha^{-1}) than last season (72,623 kg ha^{-1}), mainly because of the better climate conditions in recent year (CONAB 2017).

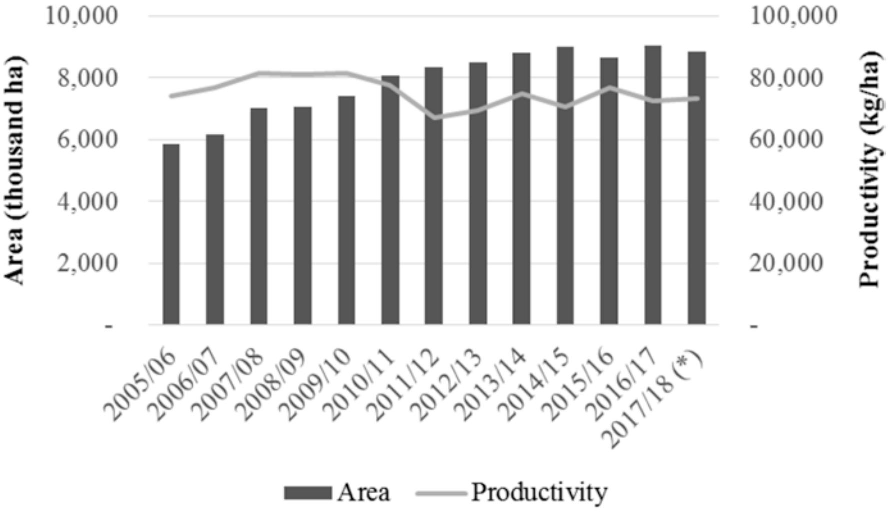

Fig. 5.1 Timeline of planted area and productivity from sugarcane crop in Brazil. (Source: CONAB 2017). ∗Values estimated

One of the reasons for the significant increase in sugarcane production after 2005 was the implementation of flex vehicle technology in the Brazilian automotive industry. Although harvested area increased until 2014/2015 (Fig. 5.1), total production did not follow the same pattern due to reduction in yield per unit area. In 2008, sugarcane energy sector suffered crisis due to the external market, which limited investments and affected the renewal of planted crop during the following years. In addition to market issues, successive droughts impacted whole Brazilian agriculture. Especially after 2011, water deficiency strongly affected sugarcane crop productivity. Moreover, implementation of mechanized harvesting, and crop expansion on poorer soil also reduced the productivity. Cane expansion on country's center-west pasture land contributed toward this decline as the soil of this area does not have promising quality as traditional sugarcane regions (Brazilian National Water Agency 2017; Meneghin and Nassar 2013).

In center-west region's Goias (GO) state, harvested area was 202.5 thousand ha in 2005/2006; however, it was recorded to be 962.6 thousand ha in 2016/2017 (375% growth in 10 years). In Mato Grosso do Sul (MS) state of the same region, harvested area expanded from 139.1 thousand ha to 619.0 thousand ha during the mentioned timeline with 345% growth. Such huge expansion is basically attributed to high prices of São Paulo's land, thus making investors and farmers search for alternative regions (Spera et al. 2017). For SP state, in 2005/06 harvested area was 3146.6 thousand ha, reaching 4773.2 thousand ha in 2016/17, with 53% growth in a decade. Regarding yield per unit area, the figures are 70,253 kg ha^{-1} (GO), 81,251 kg ha^{-1} (MS), and 77,501 kg ha^{-1} (SP) for 2016/2017 crop.

Currently, Brazilian sugarcane is destined to produce ethanol, sugar, and electricity. Another use for bagasse and straw is production of second-generation ethanol, by extracting and using the crop's carbohydrates fractions (Albarelli et al. 2014). In spite of the tremendous role sugarcane is playing in Brazil's economy, its production may be affected by environmental issues in future (Carvalho et al. 2015). Economic activities and demographic changes would remap the balance between water supply and demand among different regions of the country. In addition, climate changes entail new scenarios, cause warmer and dryer days, which may be not favorable for cultivation of many crops, including sugarcane. Additionally, environmental factors must be highlighted when considering crop expansion. Loss of biodiversity, deforestation, water bodies and air quality deterioration, increased use of chemicals and pesticides, and nutrient cycle changes must be addressed in order to avoid an irresponsible expansion (Martinelli et al. 2011).

5.2.2 The Sugar and Ethanol Industry of the Country

Sugarcane (*Saccharum* sp.) is a perennial gramineous plant of Asian origin that was brought to the Americas during the colonial period by the Spanish and Portuguese colonizers, who also explored and dominated various regions of Asia. Sugar industry has been dominated by Europe for decades; however, this scenario profoundly changed after the collapse of EU's industry during World Wars, which opened the doors for the growth of sugar industry in Brazil. In São Paulo state, the coffee culture had already been declining against sugarcane, considering both the territory and labor. The changes in the world market consolidated the region as the center of sugarcane culture. In 1953, sugar industry was modernized and organized, through the creation of the São Paulo producers' cooperative (Copersucar). Afterward in 1975, the sugarcane industry was again stimulated by *ProAlcool* program, the pioneer and largest renewable energy program ever implemented in the world.

Historically, agriculture has been playing an important role in the Brazilian economy. During the colonial period, revenue from sugar was twice than that of the gold (Machado 2017). In 2016, the agriculture sector accounted for 24% of the Brazilian GDP (Center for Advanced Studies on Applied Economics 2016). According to the Ministry of Agriculture (MAPA), Livestock and Food Supply, in May 2017, Brazilian agribusiness exports reached US$ 9.68 billion, registering a surplus of US$ 8.38 billion, higher than the same period of the previous year (by US$ 7.59 billion). The sugar and alcohol complex were the third largest item exported by agribusiness (US$ 1.08 billion), 49.2% more than the previous year. Sugar sales boosted the sector's performance to US$ 824.22 million and was 53.0% higher than in May 2016 (MAPA 2017).

The sugar industry is one of the main industrial activities in Brazil. Sugar is the main agricultural product exported to Europe on a large scale, which helps integrating Brazil with the world market (Gilio and Moraes 2016). Competitive prices in the international market led to huge investments on increasing productivity and maximizing sugar production, with the total sugar recovered expected to increase by 47.1% in the 2017/2018 harvest (the growth on the previous harvest was 45.9%).

Due to this improvement in efficiency, the total sugar production in 2017/18 harvest (38,701.9 thousand tons) is predictable to be similar to the previous harvest (38,691.1 thousand tons), despite the reduction of sugarcane farming area (CONAB 2017). In general, sugar production has been increasing steadily over the years (Fig. 5.2). After 1999, when the direct government intervention in the sugarcane industry ended, the production of sugarcane has been increasing significantly (Gilio and Moraes 2016). Between the 2000/2001 and 2009/2010 harvests, the country's sugar production doubled, from 16 million tons to 33 million tons (Union of the Industry of Sugarcane [UNICA] 2017).

Despite the growth in production, Brazilian sugar industry has experienced some difficulties in recent years. The industry operated with negative returns between 2007 and 2009 due to low sugar and ethanol prices. Also, credit availability was reduced in 2008, due to the global financial crisis. Moreover, much of the sector faced large debts due to investments in new areas of sugarcane farming and construction of new mills (Meneghin and Nassar 2013).

As Brazilian sugarcane is destined to produce ethanol, sugar, and electricity, normally the evolution in sugar production is followed by ethanol production, with the exception of some years such as the 1980s. In this period, an increase in ethanol production was significantly higher than sugar production due to the energy program *ProAlcool* (Fig. 5.2). There was a 219% increase in ethanol production, while sugar production remained practically constant (Table 5.1). After 1995 the increase in sugar production resumed. Between 2000 and 2010, sugar production increased by 135% whereas ethanol production increased by 158%. However, during 2008 and 2010, sugar production increased while ethanol production remained practically the same. Between 2010 and 2012, there was a reduction in both, but the drop in ethanol production was more drastic. In 2016/2017 harvest, there was recovery in the losses of the previous periods (38,734 thousand tons of sugar and 27,254 thousand m^3 of ethanol), which are similar in comparison to 2010 (Table 5.1).

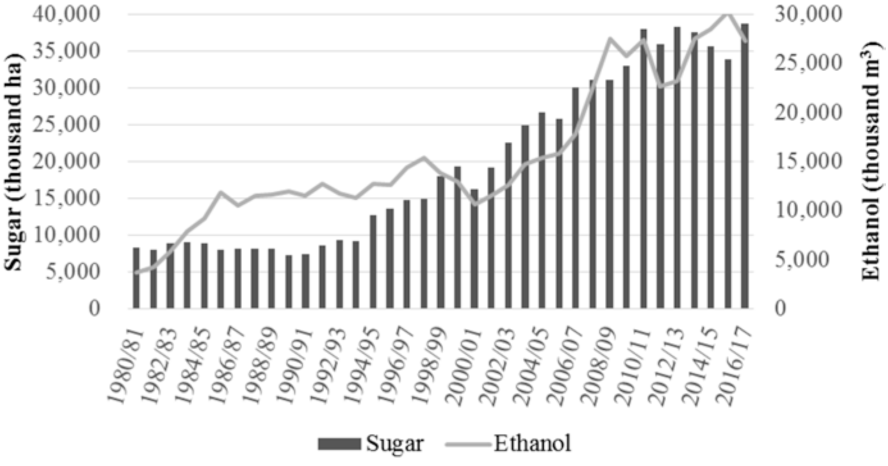

Fig. 5.2 Evolution of sugar and ethanol production in Brazil. (Source: UNICA 2017)

Table 5.1 Historical production of sugar and ethanol in Brazil

Harvest	Sugar (thousand tons)	Change (%)	Ethanol (thousand m^3)	Change (%)
1980/81	8.25	–	3.70	–
1985/86	8.03	−3	11.83	219
2000/01	16.19	102	10.59	−10
2010/11	38.00	135	27.38	158
2012/13	38.24	1	23.23	−15
2016/17	38.73	1	27.25	17

Source: UNICA (2017)
Changes are calculated considering the previous period in the table

5.3 Ethanol Production from Sugarcane in Brazil

Fuel-grade ethanol, produced from biomass, has been considered as a suitable automotive fuel for nearly a century, particularly for vehicles equipped with spark-ignition engines (technically referred to as Otto cycle engines). Ethanol came to be used in significant quantities in the 1970s. Rising oil prices during first oil crisis imposed severe exchange struggles on countries dependent on oil imports, like Brazil. As one of the main producers of sugarcane, Brazil was well situated to explore the ethanol option as an alternative to gasoline. This led the government to encourage the redirection of some sugarcane production to generate ethanol as a replacement for gasoline, thus reducing oil imports (Goldemberg 2008).

Under the Brazilian government's plan, PETROBRAS, the state-owned oil company, guaranteed the purchase of ethanol from producers. In addition, economic incentives were given to agro-industrial enterprises willing to produce ethanol, in the form of low-interest loans, which amounted to US$2.0 billion from 1980 to 1985, representing 29% of the total investment needed. On the basis of such policies, ethanol production increased rapidly over the years, reaching 18 billion liters in 2007 (Goldemberg 2008). Moreover, the Brazilian government also invested in research and development, increased investment in the agriculture sector (rural credit), encouraged mechanization of the agricultural practices, and worked on better professional qualification of stakeholders involved, in addition to emboldening the manufacturing of flex-fuel vehicles. These factors favored the development of sugar-energy sector (Pinto 2015).

Brazil is largest sugarcane ethanol producer of the world. Considering overall ethanol production, it ranks at second position with 30 billion liters of ethanol produced annually lagging only behind United States with its 50 billion liters of the ethanol per annum using corn as the major feedstock (UNICA 2017). Ethanol produced from saccharin and starch is called "first-generation". The alcohol can also be obtained from lignocellulosic materials, the so-called second-generation ethanol. In this case, agricultural and forestry residues and by-products, such as sugarcane bagasse and straw, rice straw, corn cob, etc., may be used as feedstock (Gonzalez et al. 2012; Lopes et al. 2016). Sugarcane ethanol can be produced either by chemical or microbiological processes. The chemical route is based on ethylene hydration, while the microbiological process is chiefly carried out by the yeast *Saccharomyces cerevisiae*, although other microorganisms may also be employed. The main industrial route used for ethanol production worldwide, including Brazil, is the microbiological process, also referred as alcoholic or ethanolic fermentation. In this process, sugars are converted into ethanol, energy, cellular biomass, CO_2, and other by-products by yeast cells.

The largest tropical country in the world, Brazil, stands out among the industrial economies using renewable sources in their energy matrix—attributed to its climatic conditions as the major advantage (Ruffato-Ferreira et al. 2017). Currently, Brazil has 408 sugar and ethanol plants spread throughout the country. The Southeast region, however, has the highest number of plants, with 225 plants established in this region. The sugar-energy sector corresponds to 17.5% of national energy supply (Novacana 2017a). It is noteworthy that this figure is already higher than Brazil's NDC (Nationally Determined Contribution) target of 16% for 2030.

Apart from being a source of ethanol production from sucrose fermentation, sugarcane also engenders bagasse, which is the most abundant agricultural lignocellulosic waste in the country (Castro and Pereira 2010). Bagasse can serve as an additional source of fermentable sugars, which can be converted into ethanol (Canilha et al. 2012). As Brazil produces huge amounts of bagasse every year, ethanol production from this agro-industrial waste through 2G technology is an interesting opportunity. However, production of 2G ethanol on a large scale presents a number of challenges yet, indicating the need for more R&D efforts which could heighten the profitability of this system.

Second-generation ethanol production from bagasse can increase the biofuel production in the country by 50% (Dias et al. 2013; UNICA 2017). Low lignin content is a desirable factor in plants used for the production of cellulosic ethanol, as it increases the cellulose susceptibility to enzymatic hydrolysis. Attempts are under way in this regard, and RIDESA sugarcane breeding program has selected hybrids with low lignin content or altered composition, by increasing the frequency of favorable alleles through repeated cycles of crosses and selection. The characterization of a population of experimental hybrids showed a great variation in lignin content (5–18%) in sugarcane bagasse (Loureiro et al. 2011).

In Brazil, bioethanol can be used as neat ethanol in ethanol-only and flexible-fuel vehicles (as hydrous ethanol), or blended with gasoline (as anhydrous ethanol), in proportions of usually about 25% to operate in gasoline engines. The environmental advantages of sugarcane-based ethanol, regarding gasoline substitution and greenhouse gases (GHG) emissions mitigation, have also been highlighted. However, the extent to which biofuels can displace fossil fuels depends majorly on the way in which they themselves are produced. All processing technologies involve (directly and/or indirectly) the use of fossil fuels; the benefit of biofuels displacing their fossil fuel equivalents depend on the relative magnitude of fossil fuels' input to fossil fuel savings resulting from the use of biofuel (Macedo et al. 2008). Ethanol emits lesser pollutants, and hence, the addition of ethanol to gasoline lowers the total carbon monoxide (CO), hydrocarbons, and sulfur emissions significantly. Exhaust emissions associated with ethanol are less toxic than those associated with gasoline and have lower atmospheric reactivity.

Alternative fuels, especially ethanol and biodiesel, are ranked among the most sustainable energy sources in the world, employing millions of workers. According to the International Renewable Energies Agency (IRENA), Brazil's biofuel sector generated 783 thousand jobs last year (2016), which is the highest number in global biofuels industry. Following Brazil, the United States (283,000 workers), European Union (93,000), Indonesia (154,000), Thailand (97,000), and Colombia (85,000) also lead in jobs generation in this field (Novacana 2017b).

Although bioethanol production in Brazil is considered an advanced process, there is plenty of room for improvement. The current broad interest of using very high gravity (VHG) fermentation in the industrial scenario is mainly focused in reducing production costs. It is also expected that this technology will bring benefits to the overall environmental sustainability of the process by decreasing water and energy consumption (Basso et al. 2011). This movement of technologies is fundamental to increase efficiency and reduce costs. A study conducted in 2016 showed that for every Brazilian real (R$ 1.00) invested in research and development, there is potential to return R$ 17.11 only in terms of reduction of production costs in Brazilian distilleries. Additionally, investments in scientific and technological development, and training of researchers and specialized professionals, will build solid bridges between science and industry for sustainable future of ethanol production in Brazil (Lopes et al. 2016).

5.4 Acceptance and Technological Adaptation at User's End

Brazil is widely recognized for the huge share of renewable resources in its energy matrix (approximately 48%), standing out as one of the most important members involved in bioenergy production and utilization around the world (Wilkinson and Herrera 2010). Some authors have indicated that Brazilian production and utilization of ethanol is the most successful biofuel initiative in the world (Janssen and Rutz 2011; Nardon and Aten 2008; Zapata and Nieuwenhuis 2009). The technical and economic feasibility of ethanol as a substitute of fossil fuels for transportation has been demonstrated for almost 50 years (Janssen and Rutz 2011; Zapata and Nieuwenhuis 2009). According to Du and Carriquiry (2013), as a pioneer in the production of ethanol from sugarcane juice, Brazil has successfully overcome the initial challenges of ethanol development and become a leader in bioethanol production and utilization. These authors affirmed that the low cost of production of Brazilian ethanol, considered as the lowest cost among major producing countries, is based on efficient technology for sugarcane cultivation and agricultural management, gains in ethanol production, utilization of bagasse to generate thermic and electric energy for the ethanol plant, and lower labor and input costs.

Nonetheless, Nardon and Aten (2008) proposed that Brazil's leading position on ethanol as biofuel was not the result of a long-term development strategy or visionary policies only but the outcome of a series of governmental and/or industrial decisions and reactions to the political and economic scenario of Brazil and the world. Since the beginning of *ProAlcool* (Programa Nacional do Alcool) program in 1973, the government has modified the fuel composition blending in different proportions of ethanol and gasoline according to the economic situation of various periods (Nardon and Aten 2008). Furthermore, it has also been suggested that Brazilian adoption of an ethanol-fueled transportation system was also influenced by social and cultural characteristics of Brazil.

5.4.1 **Pro-Alcool** ***Program***

In 1970s, Brazil was facing a serious economic crisis derived from the intensive increments in foreign oil prices, caused by a severe oil crisis related to the Arab oil embargo (Nardon and Aten 2008; Zapata and Nieuwenhuis 2009). Besides this, the international price of sugar reached a very low value, which affected the sugar sector in Brazil and consequently other activities linked to this sector, resulting in losses to Brazilian economy and a rise in unemployment (Zapata and Nieuwenhuis 2009). In response to the concerns about oil crisis and decline of the agricultural sector, in 1975, the military government launched the *ProAlcool* program with the aim of supporting ethanol production and gradually replacing gasoline as vehicle fuel (Barros et al. 2014; Nardon and Aten 2008; Wilkinson and Herrera 2010). The aim of the program was to boost the agriculture sector and create a new biofuel sector while reducing the country's dependence on imported oil. The long-term goal of the Brazilian government was substituting all imported gasoline with locally produced ethanol and make the country self-sufficient in energy (Zapata and Nieuwenhuis 2009). Ethanol was promoted for use in light vehicles especially adapted for alcohol; moreover, significant investments were done in sugarcane cultivation and ethanol distilleries and the establishment of a highly regulated market to guarantee the adoption of ethanol, which involved price control, high taxation to oil, obligatory supplies of ethanol at gas stations, and the subsidies (Nardon and Aten 2008; Wilkinson and Herrera 2010).

In the first phase of *ProAlcool* program, the Brazilian government made mandatory the blend of 22% of anhydrous ethanol with gasoline (E22) in the entire country. This new created demand was met by the spare capacity in sugarcane plantations and new ethanol refineries. The initial increase in refineries activity allowed testing the mechanical adaptation of the existing engines and perceiving the initial economic effects of the program. The next phase of the program was complete substitution of gasoline by ethanol in 1979, corresponding to an E100 blend, for which gasoline-powered cars were adapted to use ethanol through government's support (Nardon and Aten 2008; Zapata and Nieuwenhuis 2009). In this phase, ethanol production and utilization expanded rapidly, reaching 12 billion liters until 1986, whereas, ethanol-fueled cars represented 96% of the vehicles produced (Nardon and Aten 2008; Wilkinson and Herrera 2010; Zapata and Nieuwenhuis 2009). This intensive growth of bioethanol was facilitated by expansion of sugarcane plantation and advances in research and development on sugarcane varieties, agricultural practices and machinery, and fermentation technology (Wilkinson and Herrera 2010; Zapata and Nieuwenhuis 2009).

The third and final phase in *ProAlcool* program started in 1986 when the international oil crises ended and petroleum prices declined. The changed state of affairs diminished government's commitment to ethanol program, corresponding to gradual elimination of subsidies turning ethanol production unattractive. This variation in biofuel market resulted in supply crisis and loss of confidence in ethanol-fueled car market (Nardon and Aten 2008; Wilkinson and Herrera 2010; Zapata and Nieuwenhuis 2009). Despite the reduction in ethanol-fueled car production, which by the end of 1990s represented only 1% of the vehicles market, demand for ethanol was maintained constant by regulations requiring blend of ethanol and gasoline—resulting in ethanol imports (Nardon and Aten 2008; Wilkinson and Herrera 2010).

A renewal of the interest for ethanol production emerged in 2000s based on the increase in petroleum prices, technological advances in sugarcane sector, and particularly because of the innovation of flex-fuel cars (which could use pure gasoline, pure ethanol, or a blend of both in any proportion) (Wilkinson and Herrera 2010). In 2003, flex fuel cars were commercially launched, and immediately accepted as this technology provided customers with the option to choose between ethanol and gasoline at the gas stations (Du and Carriquiry 2013; Nardon and Aten 2008). Concomitantly, the Brazilian government established a strategic plan in 2003 to renew the investment and growth in the ethanol sector based on three reasons: to improve energy security, to maintain Brazil's position as a key player in bioenergy, and to generate employment opportunities from this industry (Badin and Godoy 2014). As a result, ethanol production and utilization increased notably in the first decade of 2000. According to Badin and Godoy (2014), during the period 2003–2008, the proportion of flex-fuel cars in Brazilian fleet increased from 4% to almost 90%. In the same period, ethanol production expanded from 15 billion liters to 25 billion liters, 80% of which was destined to be used domestically, whereas the rest was exported (Wilkinson and Herrera 2010). Since 2008, gasoline prices began to be more rigorously controlled by the Brazilian government, which hindered the upsurges in gasoline prices irrespective of variations in the international markets, and consequently affected the competitiveness of ethanol in Brazilian market (Barros et al. 2014).

5.4.2 Consumer Acceptance of Ethanol

Ribeiro (2013) stated that consumer's acceptance of biofuels varies among different geographical and cultural contexts, and it is highly influenced by media discourse as well. In Brazil, public acceptance played an invaluable role in the dynamic history of ethanol as a biofuel (Zapata and Nieuwenhuis 2009). During different phases of the *ProAlcool* program, the trust of the consumer was continuously both promoted and reduced by the government and industry decisions (Zapata and Nieuwenhuis 2009). The lack of government commitment to ethanol production and utilization caused loss of confidence among consumer during third phase of the program, while the emergence of flex-fuel cars renewed consumer acceptance (Zapata and Nieuwenhuis 2009). Public acceptance has been influenced by the social perception of ethanol technology regarding both production and utilization, supply and availability of ethanol in gas stations, and price of this biofuel in comparison with the gasoline (Zapata and Nieuwenhuis 2009).

Regarding public perception, it is important to point out that consumers have traditionally considered gasoline as reliable fuel, which increases ethanol's attractiveness when gasoline price remains stable and/or low enough (Zapata and Nieuwenhuis 2009). In the beginning of *ProAlcool* program, there were public concerns about the sustainability of ethanol produced from sugarcane, because of the emissions and waste generated during cultivation and processing, and the imported oil was considered a cleaner alternative (Zapata and Nieuwenhuis 2009). Nonetheless, during the second phase, ethanol benefits compared to gasoline became more evident, and environmental agenda around ethanol started to play a more prominent role (Zapata and Nieuwenhuis 2009). Phalan (2009) stated that acceptance of biofuels is increasing as a function of the social preference for environmentally friendly products. Nevertheless, according to Barros et al. (2014), despite the increasing knowledge and dissemination of ethanol benefits in comparison with fossil fuels, some Brazilian consumers still have doubts about the replacement of gasoline.

Zapata and Nieuwenhuis (2009) stated that public awareness and acceptance of biofuels have been reinforced by the environmental concerns related to fossil fuels, allied with a clearer understanding of the political and social implications of economies based on these fuels. Barros et al. (2014) also proposed that the global market will experience growth in ethanol consumption because of growing environmental trepidations around the world. This is in accordance with Brazil's strategic interests to be a leader in the promotion of a global ethanol market and a key player in international discussions about the impact of ethanol on environmental and social sustainability, and energy and food security, among others (Wilkinson and Herrera 2010).

Comparative prices of ethanol and gasoline have been one of the most important factors for Brazilian consumers to select the fuel as well as the vehicle type. Before 2003, the consumer had to choose between buying an ethanol- or gasoline-fueled car based on the relative prices of these fuels, which constituted an investment risk (Ribeiro 2013; Zapata and Nieuwenhuis 2009). Since 2003, the flex-fuel car technology allowed the immediate selection between these fuels at the gas station, which reduced consumer risk and concerns about supply stability (Ribeiro 2013; Zapata and Nieuwenhuis 2009). Consumers who buy flex-fuel cars tend to choose ethanol over gasoline when ethanol price does not exceed 70% of the price of gasoline at the pump; otherwise, gasoline is more economical (Badin and Godoy 2014; Ribeiro 2013; Zapata and Nieuwenhuis 2009). According to Badin and Godoy (2014), ethanol consumption may be negatively affected by gasoline prices control; therefore policies, such as tax reduction for ethanol production and consumption, may be necessary to restore ethanol competitiveness.

Last but not least, public perception of the sugarcane agroindustry has also influenced the consumers' acceptance of ethanol as biofuel. According to Badin and Godoy (2014), the expansion of the sugarcane cultivation necessary for ethanol production since *ProAlcool* has been target of criticism, due to potential negative environmental and social effects such as deforestation, burning harvest, poor working conditions, and even child labor (Badin and Godoy 2014; Rodrigues and Ortiz 2006). It is important to point out that sugarcane occupies only 1% of the total arable land in Brazil and 5% of the land dedicated to crops (Wilkinson and Herrera 2010). Nevertheless, sustainability debates have already started about the potential effect of sugarcane expansion on the Amazon and Cerrado deforestation. In spite of the fact that sugarcane cultivation is not suitable in the Amazon because of the climatic conditions (Goldemberg and Guardabassi 2009), it is proposed that expansion of this crop could affect soybean and corn plantation and livestock in this region (Janssen and Rutz 2011).

Both environmental and social problems have been associated with traditional manual harvest of sugarcane; because of the poor working conditions of the cane-cutters and emissions generated from burning of the cane straw (Janssen and Rutz 2011; Wilkinson and Herrera 2010). According to Wilkinson and Herrera (2010), the working conditions of the cane-cutters have been continuously exposed by various civil organizations and the media. In response to social pressure, improvements have been introduced through recent laws for better working conditions, increased wages, better schooling, and the discouragement of child labor (Janssen and Rutz 2011; Wilkinson and Herrera 2010). Furthermore, the environmental problems of manual harvest are being dealt using mechanical harvesting, which does not require eventual straw burning and is expected to increase the environmental sustainability of sugarcane cultivation (Leal et al. 2013).

Besides the abovementioned factors affecting public acceptance of ethanol, cane biofuels could face public resistance in the future if technological improvements do not advance as forecasted, e.g., evolving second-generation ethanol with improved cost-benefit ratio and environmental efficiency (Luk et al. 2010). Moreover, public acceptance of genetically modified sugarcane, which is an important aspect for advanced ethanol production, will also dictate the consumer response (Fischer et al. 2010; Gallardo and Bond 2011).

5.5 The Biofuels Economy of the Country

Sugarcane-derived ethanol is considered a green fuel as it is produced by renewable and less polluting sources, thus having limited impact on Earth's atmosphere. Besides environmental aspects, the use of ethanol as a fuel can also economically favor several countries dependent on import of gasoline. Self-sufficient ethanol-producing countries can save huge foreign exchange spent on oil imports. In addition, it is also perceived that ethanol production directly influences the labor market, generating between 15 and 21 times more jobs than the opportunities generated from equivalent oil production (Goldemberg 2010; Lucon and Goldemberg 2009; SECEX – Foreign Trade Department 2017).

Brazil's ethanol-based economy started evolving since 1930s, being the first large-scale production plant of anhydrous ethanol installed in Brazil in 1931. Between 1930 and 1970, the Brazilian sugarcane industry oscillated between surplus and deficits, and during this time, it was always under state intervention (National Institute for Applied Economic Research 2010). In 1970s, the international oil crisis once again highlighted the important role ethanol could play in the national economic scenario. Between 1985 and 1999, even with the popularization of cars fueled with alcohol, *ProAlcool* stayed stagnant. After several crises debilitated the program, the government halted funding and subsidies, which led to shutdown of some units. *ProAlcool* continued as an alternative energy and gasoline replacement plan but with poor prospects and institutional problems. During the period 2002–2007, *ProAlcool* program was reactivated due to high prices of oil, the environmental appeals of the Kyoto Protocol, and the emergence of flex-fuel vehicles (Cruz et al. 2012; Mendonça 2008; Michellon et al. 2008). In 2008, the sugar and alcohol industry began to experience difficulties again due to the International Recession and the closure of the commodities cycle in Brazil. During this time, the expectations of pre-salt oil reserves and the decrease in bank credit deepened the crisis (Globo 2016). Even with a problematic scenario for the industry, in 2012, GRANBIO Company inaugurated the first Brazilian second-generation ethanol plant in the Northeast region (Novacana 2013).

The production of sugarcane and ethanol, despite being on the rise in Brazil, suffered from financial market disparities and the global political momentum (Fig. 5.3). However, the sector kept progressing as the main producer of ethanol from sugarcane

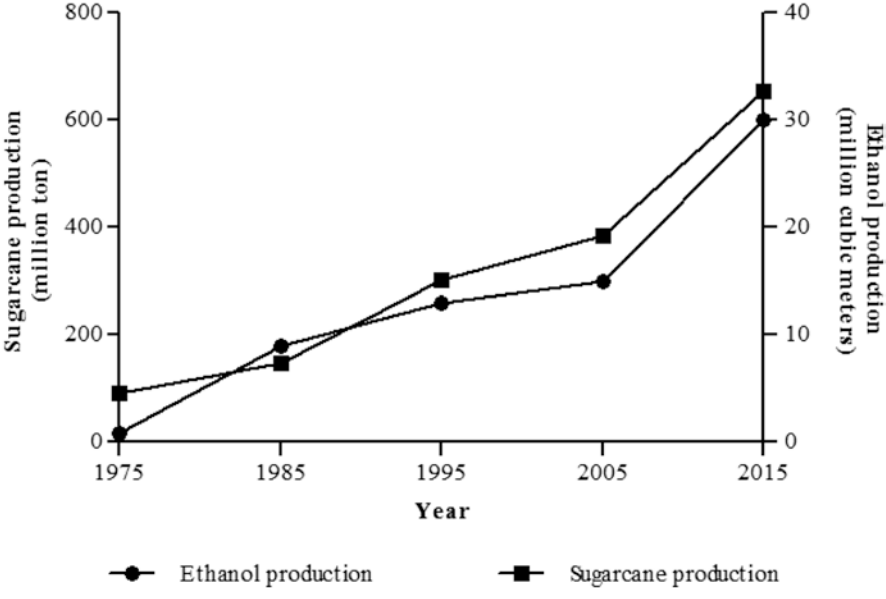

Fig. 5.3 Evolution of sugarcane and ethanol production in Brazil from 1975 to 2015. (Source: MAPA 2017)

and is on its way to develop new technologies for enhancing the production of this important biofuel.

5.6 Feasibility of Sugarcane Crop for Brazil

Brazil is fifth largest country with respect to total area. There are numerous factors which support country's agriculture sector. The country has climatic conditions varying from tropical to subtropical, and it is blessed with extensive river basins (International Energy Agency 2006). The warm climatic conditions in conjunction with regular rainfalls, plenty of solar energy, and almost 13% of the potable water available on the earth are promising conditions for agricultural productivity.

Abundance of natural resources and agricultural land availability have assisted Brazil to become the highest sugarcane producer (Goldemberg et al. 2014; Nass et al. 2007). Moreover, several years of expertise and heavy government's investments in this field have also contributed toward ranking Brazil at the top position (Marin and Nassif 2013). In general, Brazilian weather favors sugarcane cultivation because of high precipitation volume well distributed all over the year, even if the dry season compromises the photosynthetic rate and, consequently, the biomass accumulation (Marin and Nassif 2013).

*Companhia Nacional de Abasteciment*o (CONAB) monitors the sugarcane production in Brazil. Variations in sugarcane harvest and ethanol production are expected each season and are usually related to climatic and economic conditions (Table 5.2). It has been seen that ethanol production declined by 4.9% in 2017/18 season, mainly because of the increase in gasoline consumption, and upsurge in sugar demand (CONAB 2017). Brazil stands at a remarkably better position when compared to the main sugarcane-producing countries in terms of harvested area and sugarcane production, while its yield per unit area can be compared to that of China and India (Fig. 5.4) (FAO 2014).

Regarding the range of biomass sources that can be utilized to produce bioethanol besides sugarcane, corn and sugar beet have been described as the main productive crops, either in terms of ethanol yields or in terms of productivity per unit area. However, biomass from other crops can also be used since they have considerable sugar or starch content, for example, sweet sorghum, cassava, wheat, and rye (Manochio et al. 2017).

Table 5.2 Territorial area destined to sugarcane, sugarcane productivity, and ethanol production in Brazil (season 2016/2017 and 2017/2018)

Sugarcane harvest data and ethanol production	2016/2017 season	2017/2018 season	Variation
Territorial area destined to sugarcane (ha)	9049.2	8838.6	−2.3%
Sugarcane productivity (kg ha^{-1})	72,623	73,273	+0.9%
Ethanol production (×10^3 L)	27,807,523	26,451,194.3	−4.9%

Source: CONAB (2017)

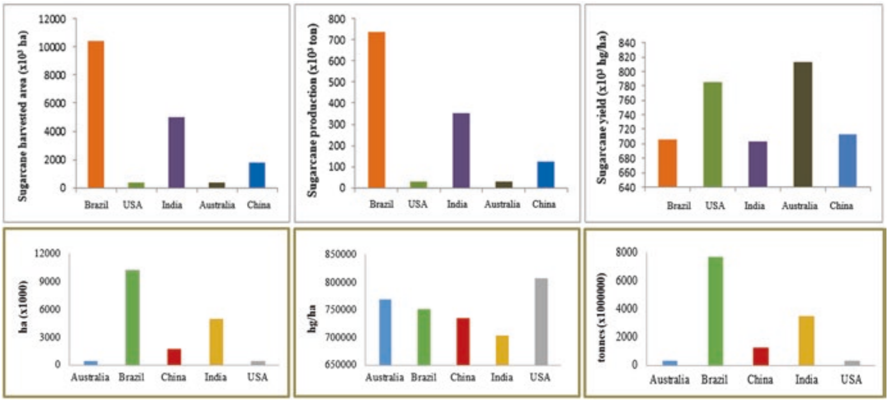

Fig. 5.4 Sugarcane area (ha), production (ton), and yield (hg ha^{-1}) for the major global producers in 2016. (Source: FAO 2016)

Compared to corn and sugar beet ethanol, which are mainly produced in USA and European Union, respectively, sugarcane leads to a higher yield per hectare. From corn, it is possible to achieve 4180 L ha^{-1}, while the yield from sugar beet is 5500 L ha^{-1}; the ethanol yield from sugarcane, on the other hand, is equivalent to 6470 L ha^{-1} (Goldemberg and Guardabassi 2009). Besides higher productivity, usually, the process of bioethanol engenderment from sugarcane is simpler. Sugars (e.g., from sugarcane, sugar beets, molasses, and fruits) can be converted into ethanol directly, while starches (e.g., from corn, cassava, potatoes, and root crops) require a preliminary step of hydrolysis to fermentable sugars using enzymes from malt or molds, requiring an additional step in the process. Once simple sugars are formed, enzymes (amylases to depolymerize the polysaccharide into glucose monomers) from microorganisms can readily ferment them to ethanol (Lin and Tanaka 2006).

The extensive Brazilian know-how in the field of bioethanol production from sugarcane allows the country to enjoy one of the lowest production costs, i.e., US$ 0.24–0.42 L^{-1} (Manochio et al. 2017). Table 5.3 summarizes some important characteristics about Brazilian ethanol production in this regard. Apart from economic advantages, important environmental benefits are also noted for employing sugarcane crop for the purpose against sugar beet and corn. Brazilian sugarcane ethanol presents higher percentage of avoided GHG emissions (69–89%) as compared to corn (30–38%) and sugar beet (35–56%) (Manochio et al. 2017).

Sugarcane is also considered a better choice in terms of cultivation because it can be grown without a competition with crops destined to human feeding. Corn planting, on the other hand, usually uses the same land resources as soybean crops; thus, the expansion of this crop can be a threat to food security (Goldemberg and Guardabassi 2009). The use of bagasse for second-generation ethanol production or other bioproducts of interest, and thermoelectric energy production, can make the whole use of the sugarcane possible in a biorefinery configuration—

Table 5.3 Major characteristics of ethanol production from sugarcane in Brazil

Characteristics	Value	Reference
Productivity per area (ton ha^{-1})	60–120	Brazilian Development Bank (2008)
Production cost (US\$ L^{-1} ethanol)	0.24–0.42	Manochio et al. (2017)
GHG emissions (kg CO_{2eq} L^{-1} ethanol)[a]	0.25	
Avoided emissions of GHG (%)	69–89	
Total production (billion L) (D)	22.5	Goldemberg and Guardabassi (2009)
Area cultivated (million ha) (E)	3.4	
Energy balance	8.1–10	
Yield (L ha^{-1}) (D/E)	6.471	

[a] *GHG* greenhouse gases

increasing the yield of ethanol engenderment and enhancing the process outputs (Mendes et al. 2017).

A disadvantage of Brazil's sugarcane compared to corn is that the first crop cannot be harvested during the rainy season, while the second one can be reaped during the whole year. To cope with this issue, modern Brazilian distilleries are also structured to ferment corn starch or to combine the fermentation of sugarcane molasses and starchy biomasses in the off-season, thus providing the units with the ability to operate throughout the year.

5.7 Capacity, Potential, and Future Perspectives

Currently, biofuel production has a worldwide market demand and is linked to international priorities and social necessities. Additionally, sustainable development, enhanced agricultural production, energy independence, and CO_2 reduction, among others, are also issues of national sovereignty for guaranteeing a renewable and continuous source of energy, lowering environmental problems, and ensuring population's quality of life. Therefore, investments aiming the development and enhancement of new strategies and technologies to improve biofuel production from sugarcane and other sources are a necessity, not only for Brazil but for other countries too.

In 2009, the Brazilian Ministry of Agriculture, Livestock and Food Supply passed a directive to establish an agroecological zone for sugarcane cultivation in Brazil. The major aim of this directive was to overlook the sugarcane expansion over country's territory, conforming the norms of sustainability. Approximately 66 million ha of the Brazilian territory was deemed suitable for extending sugarcane cultivation; the area corresponded to approximately 8% of the total national territory (Marin and Nassif 2013).

In the past 30 years, number of sugarcane varieties in Brazil increased from 6 to more than 500; however, researches aiming the development of GMO crops were still delayed, mainly due to legal restrictions and the consumers' concerns

(Goldemberg and Guardabassi 2009). Even facing many barriers, Brazilian biotechnology made a recent and significant progress: on June of 2017, Brazil's biosecurity committee (CTNBio) approved the field production of the first transgenic sugarcane variety. It was developed by CTC (Centro de Tecnologia Canavieira) and was modified to have resistance to the sugarcane borer, *Diatraeasaccharalis* (Brazilian National Bank for Sustainable and Social Development [BNDES] and Brazilian Center of Management and Strategic Studies [CGEE] 2008). Moreover, use of biotechnology to introduce new characteristics to the agriculture systems, e.g., drought tolerance, soil acidity, and salinity tolerance, increased nutrient uptake efficiency, and the development of technologies to promote symbiotic nitrogen fixation is also being investigated (MAPA 2006, MAPA 2009).

Considering biotechnological approaches, another possible improvement relates to microorganisms involved in bioethanol production. On one hand, there is search for tailored-yeast strains that could favor fermentation by increasing the ethanol yields, and on the other hand, strains for bioconversion of broader number of substrates are being investigated (Lopes et al. 2016; Neves et al. 2007). Advances in bioethanol production may also be achieved by the development of new technologies regarding the fermentation process. As described by Neves et al. (2007), for example, cell immobilization can result in higher process stability, facilitate downstream processes, and lead to higher ethanol titers, when compared to free cell processes. Another favorable technical approach is to perform the fermentation in a fed-batch system, which could increase the process yield and reduce the bacterial contamination (Lopes et al. 2016).

Moreover, another prospective improvement in bioethanol production is, certainly, biomass exploitation for second-generation ethanol. Since most of the biomass utilized for 2G ethanol is derived from agricultural wastes and subproducts, this approach does not compete with food production (Goldemberg et al. 2014). The usage of biomass-derived sugars is also an opportunity for the production of other biofuels, namely, isobutanol and butanol, which can contribute toward the biorefinery concept of sugarcane (Lopes et al. 2016). Development of efficient and cost-effective 2G ethanol production processes is crucial not just to reduce the pressure on cultivable lands, but also to augment the bioethanol production capacity and to harvest more profits from sugarcane crop. An increase in the international sugar demand affects the ethanol production negatively; however, this issue is expected to be dealt through equipping the mills with option to use other vegetal feedstocks in case of unavailability of sugarcane for the purpose (Luz et al. 2009).

The socioeconomic development of the country reflects from improvement of living conditions of rural communities (Caldwell 2007). Regarding work conditions and possible alterations in the labor market, a general analysis elaborated by Chagas (2014) emphasized that the main negative impact on increasing bioethanol production is related to the heavy manual work involved in sugarcane harvest, which is also considered to give rise to various health issues, e.g., permanent injuries, and harms associated with ergonomic risk factors. Nonetheless, the number of workers employed in the manual harvesting is diminishing due to the adoption of harvest mechanization. A relevant and positive consequence of the expansion of this sector is, as described by Chagas (2014), an increase in the municipal revenues, which could promote a virtuous cycle of socioeconomic benefits for developing regions, and in author's opinion, the generated benefits could be enough to level the negative impacts of this agroindustry.

Bioethanol is cleaner than fossil fuels and increasing its consumption is a valid approach to reduce CO_2 and GHG emissions. For instance, in Brazil, between 1973 and 2000, the use of ethanol blended with gasoline or as a neat-fuel resulted in a significant reduction in CO_2 emissions (Neves et al. 2007). However, one of the main side effects of cane bioethanol production in Brazil is deforestation: the expansion of sugarcane crops can take over pasture land, forcing cattle breeding to be transferred to cheaper areas, like the Amazon forest (Goldemberg and Guardabassi 2009). The country has to focus on developing and executing strategies to minimize this risk, such as regenerating already degraded pasture areas, and utilizing integrated crop-livestock systems (ICLS) would help (Ferreira et al. 2012; Goldemberg et al. 2014).

5.8 Conclusion

As a closure to this topic, the development of bioethanol-based fuels industry in Brazil has a large potential to favor the country not only in socioeconomic terms but also as a lift toward energy security and sustainability goals of reducing CO_2 and GHG emissions. Reaching all these benefits by exploiting full potential of sugarcane crop will be more productive and profitable through improved management practices, agroecological zoning, higher process efficiencies, and changes in the land use directives.

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Chapter 6
Sugarcane Production and Its Utilization as a Biofuel in India: Status, Perspectives, and Current Policy

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6.1 Introduction

Global demand for fuel efficiency, environmental quality, energy security, and the rise of oil prices has elicited worldwide attention to alternative fuels from renewable sources. In this context, the world is searching for alternatives of fossil fuels which could provide energy in a reliable, constant, and sustainable manner. One of the alternatives for fossil fuels is biofuels. Many countries have adopted to move from conventional fuels to biofuels considering them sustainable substitute. Biofuels are

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renewable liquid fuels produced from biomass (biological raw materials). They are cost-effective, ecofriendly, and have potential to be a good replacement for transportation fuels like petroleum, diesel, and jet fuel (Bandyopadhyay 2015). Moreover, biofuels are also favorable alternatives because they can be produced domestically saving the foreign exchange in import of gasoline. Therefore, developing countries like India are emphasizing on substitution of petroleum products through biofuels (Union Ministry of New & Renewable Energy [MNRE] 2009; Government of India [GoI] 2016).

Biofuels are also gaining more interest to ensure energy security and tackle fossil fuels' related health hazards and global warming (Goldemberg et al. 2008). Worldwide, about 40% of the biofuel production is derived from sugarcane (Talukdar et al. 2017). Sugarcane ethanol is an alcohol-based biofuel which is produced by the fermentation of sugarcane juice and molasses. Sugarcane, as a potential energy feedstock, can maintain the ecological balance by strengthening the industries and contributing to diversification of energy sources around the globe (Eric Lam et al. 2009).

Brazil and USA are the leading ethanol producers as they have adopted vigorous policies for boosting ethanol engenderment to reduce dependence on fossil fuels. India needs to adopt similar policy measures as it targets to rapidly expand the use of cleaner, safe, and greener alternatives in transportation. India is the second largest producer of sugarcane and is ranked fourth in ethanol production after the United States of America (USA), Brazil, and China, with ethanol production of about 1900 million liters and a distillation capacity of 2900 million liters per annum (Gonsalves 2006; GoI 2016).

Sugarcane (*Saccharum* spp.) is a perennial grass (Fig. 6.1) which stores its carbohydrate reserves as sucrose. This crop supplies about 70% of the sugar needs of the world's population. It is indigenously grown in India and is primary source of sugar, khandsari, and gur. About two-third of the total sugarcane cultivated in the country is used for making khandsari and gur and the remaining one-third goes to sugarcane mills. It is also used as raw material for manufacturing local liquors. Additionally, as commented earlier, sugarcane also serves as a biofuels source in India. This chapter details the current status of sugarcane production, national policies regarding biofuels, blending requirements, future perspectives, and the challenges related to the same, in India.

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Fig. 6.1 With standing sugarcane crop of Balrampur village in West Medinipur district of West Bengal Province of India

6.2 Status of the Sugarcane Crop in India

Sugarcane is a principal commercial crop that is grown in the subtropical and tropical regions of the country. India has the largest area under the sugarcane cultivation throughout the globe and is second largest producer next only to Brazil. In India, sugarcane production and sugar industry play an important role in socioeconomic development in rural areas by utilizing resources and creating job opportunities and higher income as well. About 8.0% of the agricultural population and about 45 million sugarcane farmers, their dependents, and oversized population of agricultural labor are associated with sugarcane cultivation, harvesting, and accessory activities in India. Sugarcane accounts for the largest value of production in the country and holds top position among other commercial crops. It is a popular choice for cultivation among farmers wherever geographical and climatic conditions favor its growth. In India, nine states are growing sugarcane on a large area with different varieties depending on the properties of the soil and agroclimatic conditions. A number of varieties are available and developed commercially for sugarcane cultivation keeping in view these factors for various states of the country (Table 6.1). For instance, as proposed by Indian Institute of Sugarcane Research (IISR 2018) and Sugarcane Breeding Institute Coimbatore (SBI 2018), the best suitable varieties of sugarcane are CoC671 and Co86032 and Co86032 for Maharashtra and Tamil Nadu states, respectively, released for higher productivity and sugar recovery.

Sugarcane is grown primarily in the two distinct agroclimatic zones of the southern hemisphere, i.e., tropical and subtropical. Tropical regions (Andhra Pradesh, Gujarat, Goa, Madhya Pradesh, Karnataka, Tamil Nadu, Kerala, Pondicherry, and Maharashtra) shared about 55% of the total sugarcane cultivation area and

Table 6.1 Commercially developed sugarcane varieties for cultivation in different states of India

States	Released suitable sugarcane varieties
Andhra Pradesh	Co-8504, CoA07706, CoA-8801, CoA89082, CoC-85038, and CoV-92103
Assam	Cajor-1 and 2, Co- 8315, Co BLN-9102, Co BLN-9130, Co-1008, Co-1132, and Co-6907
Bihar	Bo-104, Bo-106, Bo-109, Bo-128, Bo-90, Bo-99, C0S-87268, and CoS-767
Gujarat	Co-671, Co-8021, Co-85004, Co-86032, CoC-86008, and CoLK8001
Haryana	Co-7717, Co-975, CoJ-58, CoJ-64, CoJ-83, CoLK-8001, CoS-767, and CoS-8436
Karnataka	Co-8011, Co-86032, Co-87044 Co-91002, and CoC-671
Maharashtra	Co-8014, Co-85004 Co-86032, and CoC-671
Tamil Nadu	Co-86032, Co-86249, CoC-671, CoC-93076, CoC-95071, and CoJ-86141
Uttar Pradesh	CoPlant-84211, CoS-687, CoS-767, CoS7918, CoS-802, CoS-8315, CoS-8432, and CoS-87216

Sources: SBI (2018) and IISR (2018)

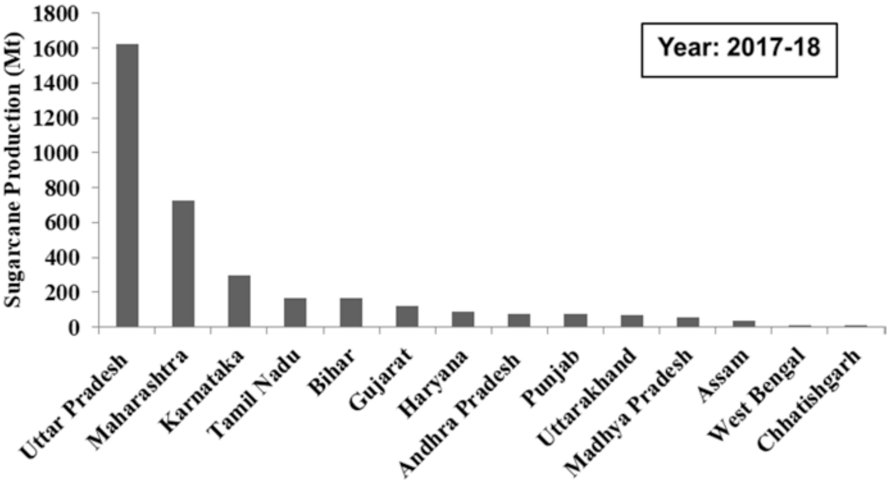


Fig. 6.2 Statewise sugarcane production in 2017–2018. (Bar diagram modified from DSD 2018)

production, whereas subtropical regions (Uttar Pradesh, Bihar, Haryana, and Punjab) accounted for 45% of total cultivation area and production of sugarcane in the country. Statewise production indicates that more than 80% of sugar comes from only four states, viz., Uttar Pradesh, Maharashtra, Karnataka, and Tamil Nadu (Directorate of Sugarcane Development [DSD] 2018). Uttar Pradesh province of the country representing the lead production of sugarcane (Fig. 6.2) was estimated to have the highest area of sugarcane with 23.40 M ha in 2017–2018 as per report of *The Economic Times* (Bhosale 2018). According to the production capacity of sugar, the states are classified into three groups as presented in Table 6.2.

Table 6.2 Classification of sugar-producing states in India

Groups	Types of production capacity	Examples
First groups	High sugar producing	Maharashtra and Uttar Pradesh
Second groups	Medium sugar producing	Gujarat, Andhra Pradesh, Tamil Nadu, Karnataka, and Haryana
Third groups	Low sugar producing	Bihar and Assam

In the year 2017–2018, sugarcane production was 355.09 million tonnes out of this 234.975 million tonnes that were harvested by the two largest producers, viz., Uttar Pradesh and Maharashtra (Table 6.3). The lowest sugarcane production was 0.122 million tonnes by Kerala. However, sugarcane productivity was highest in Kerala which recorded per hectare yield of 116.2 t (DSD 2018). In the year 2014–2015, the total production, i.e., 362.33 million tonnes, was recorded, whereas in the year 2015–2016, the estimate was 348.4 million tonnes, whereas total production of sugarcane in the current year 2018/2019 is expected to rise to 415 million tonnes on 5.2 M ha of area (Table 6.4). The sugarcane yield in India has increased to 79.81 tonnes ha^{-1} from 70.09 tonnes ha^{-1} during the period from 2010–2011 to 2018–2019 (Landry and Aradhey 2018).

6.3 The Sugar Industry of the Country

Sugar industry is one of the most important agro-based industries and has a significant contribution toward the socioeconomic development of India. It is considered as the 2nd largest agricultural-based industry following only the cotton and textile industry. Indian sugar industry is playing major role in economic development of the rural population through utilization of domestic resources and creation of employment opportunities. Approximately 0.5 M people of the country are dependent completely on sugar factories for their livelihood, while ~50 M farmers and 7.5% of the total rural population are associated with cultivation, harvesting, production, and ancillary activities of sugarcane crop (Ghanekar 2014).

Most of the sugar mills are situated in main sugarcane-growing states including Uttar Pradesh, Maharashtra, Karnataka, Tamil Nadu, Andhra Pradesh, and Gujarat. About 25% of the overall sugar production is done by Maharashtra, while Uttar Pradesh contributes by 24% (Bhosale 2018). Currently, there are 703 sugar factories in the country. Among them, 325 mills are operated by the cooperative sector, 335 by private sector, and 43 by public sector. Half of the operational sugar mills are situated in Maharashtra. The motto of these factories is to upgrade the rural areas of the nation, which they are excellently contributing for (Indian Sugar Mills Association 2008; Landry and Aradhey 2018).

The sugar industry has great relevance to the economy of India, as it saves huge amounts of foreign exchange by domestically fulfilling the sugar requirements of

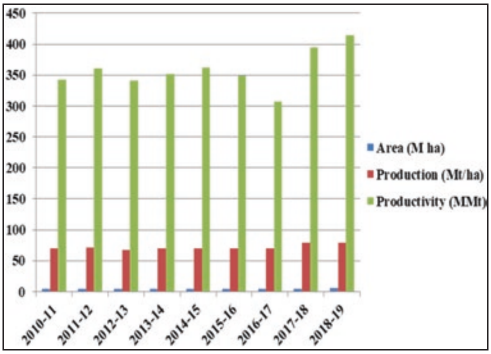
Table 6.3 Region-wise status of major sugarcane-producing states of tropical and subtropical regions in India

Sugarcane-producing states	2015–2016			2016–2017			2017–2018		
	Area (×00000 ha)	Production (×00000 tonnes)	Productivity (tonnes ha^{-1})	Area (×00000 ha)	Production (×00000 tonnes)	Productivity (tonnes ha^{-1})	Area (×00000 ha)	Production (×00000 tonnes)	Productivity (tonnes ha^{-1})
A. Tropical region									
Andhra Pradesh	1.22	93.53	76.70	1.03	78.30	76.00	0.99	79.48	80.30
Gujarat	1.57	111.20	70.80	1.69	119.50	70.70	1.84	122.34	66.50
Karnataka	4.50	378.34	84.10	3.97	273.78	69.00	3.70	299.02	80.80
Kerala	0.01	1.38	101.40	0.01	1.14	114.00	0.01	1.22	116.20
Madhya Pradesh	1.03	52.81	51.30	0.92	47.3 0	51.40	0.98	54.30	55.40
Maharashtra	9.87	736.80	74.70	6.33	522.62	82.60	9.02	726.37	80.50
Tamil Nadu	2.52	254.94	101.10	2.18	189.88	87.10	1.83	165.62	90.10
B. Subtropical region									
Assam	0.29	10.38	35.30	0.32	12.07	37.70	0.30	37.20	11.15
Bihar	2.44	126.49	51.80	2.40	130.36	54.30	2.43	165.11	67.90
Chhattisgarh	0.36	0.68	1.90	0.21	8.48	40.40	0.30	12.47	41.60
Haryana	0.93	66.92	71.90	1.02	82.23	80.60	1.14	87.29	76.60
Jharkhand	0.10	7.09	69.50	0.07	5.13	73.30	0.07	5.23	69.80
Odisha	0.09	5.77	64.40	0.05	3.44	68.80	0.05	3.41	64.40
Punjab	0.90	66.07	73.40	0.88	71.52	81.30	0.93	75.33	81.00
Rajasthan	0.06	5.31	86.50	0.07	4.89	69.90	0.05	4.04	74.50
Uttar Pradesh	21.69	1453.85	67.00	21.60	1401.69	64.90	22.34	1623.38	72.70
Uttarakhand	0.97	58.86	60.80	0.93	64.77	69.60	1.02	71.42	70.00
West Bengal	0.17	20.75	119.20	0.21	15.50	73.80	0.17	12.94	76.10

Sources: Modified from DSD (2018)

Table 6.4 Year-wise status of area, production, and productivity of sugarcane in India since 2010

Year	Area (Million ha)	Production (Metric ton ha^{-1})	Productivity (Million Metric ton)
2010-11	4.89	70.09	342.38
2011-12	5.08	71.07	361.03
2012-13	5.06	67.38	341.20
2013-14	5.01	70.26	352.14
2014-15	5.14	70.44	362.33
2015-16	4.96	70.25	348.40
2016-17	4.38	70.02	306.70
2017-18	4.95	79.80	395.00
2018-19	5.20	79.81	415.00



Source: Landry and Aradhey (2018)

the country. The sugar industry also acts as a leading representative in the national and international trade as India produces 15% of the global sugar (from its 25% share of the global sugarcane production). The sugarcane sector of the country harvests approximately 300–350 million metric tonnes (MMts) sugarcane, 30–36 MMts white sugar, and 6–8 MMts jaggery and khandasri, annually. Moreover, the Indian sugar industry is producing 2300 MW power, and 2700 ML of alcohol and other allied products from this crop (Venkatesh and Venkateswarlu 2017).

Sugarcane is a rich source of sucrose, cellulose, fuel, and numerous chemicals. Various products and coproducts of sugar industry include sugar, bioethanol, electricity, paper, biomanure, and board, besides other ancillary products. Hence, the by-products of sugar industry like bagasse, molasses, and press mud also play important role toward national economy by promoting a number of supplementary industries (Gangwar 2014). About 45–55% total sugar content is found in molasses which is used as a raw material for manufacturing many value-added products such as ethanol, acetone-butanol, citric acid, lactic acid, lysine, oxalic acid, etc. Apart from industrial products and by-products, the green leaves, tops, and trash from sugarcane crop are important cattle feed and preferred for the purpose in rural areas in India.

Bagasse is a fibrous residue that is left after the crushing of sugarcane. It can also be used as fuel in the boilers of sugar factory for fulfilling the steam requirements for power generation, whereas its raw material may be used as an alternative for wood pulp. The ethanol demand of the country is already high, and increasing day by day. The contribution of sugar industry is about 1% in the GDP of Indian economy. The annual turnover of the Indian sugar industry was estimated to be US$5.669 billion, while the amount of taxes collected from this sector by the government was estimated to be US$ 345.685 million for the year 2017 (Venkatesh and Venkateswarlu 2017).

6.4 Current Status of Cane Bioenergy Production in India

Initiatives have been taken in many countries of the world to use energy from renewable biomass sources for energy security, socioeconomic benefits, and environmental advantages. Biofuels not only have the potential to meet energy requirements indigenously, but they also have positive impacts on elimination of lead compounds present in petrol and on reduction of toxic emission of dangerous GHS gases (Goldemberg et al. 2008). Against the fossil fuels, there are many renewable alternatives available; however, ethanol has emerged as one of the preferred options for the transportation purposes in India (Gopinathan and Sudhakaran 2009).

Till date, in India, several initiatives have been taken toward energy security. India meets 70% of its fuel needs through imports. Bioenergy constitutes an appropriate alternate energy source for developing countries like India as huge amounts of raw material (biomass) are available (Mishra 2006). Apart from fuel ethanol, India has also developed bioenergy-based technologies that could fulfill the electricity and cooking energy requirements through small biomass gasifiers. Being a developing economy, India offers a tremendous potential to explore eco-friendly, sustainable, and cost-effective bioenergy technologies (bioenergy and biofuels) (Sudha et al. 2003).

Sugarcane is a key player for food security because nearly 75% of the world's sugar comes from sugarcane plantation (De Souza et al. 2008). The sugar extracts obtained from sugarcane can also be used in fermentation process for ethanol production and other value-added products, whereas bagasse can be utilized by sugar mills for steam and power generation (Talukdar et al. 2017). Currently, about 1.3 billion liters of ethanol are produced by India from cane molasses, while it has an installed capacity of 3.2 billion liters for the same. Annually, about 121 GJ fuel ethanol is produced from sugarcane (Blanchard et al. 2015). Hence, sugarcane (molasses and juice) is an important feedstock for sugar and ethanol production, and electricity generation in India, apart from being a major cash crop of the country (Fig. 6.3).

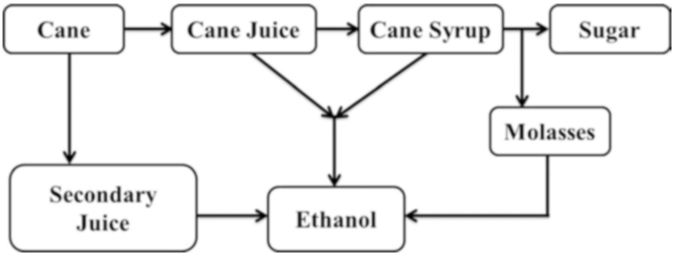


Fig. 6.3 Process flow diagram of ethanol production from sugarcane in India

6.5 Capacity, Potential, and Future Perspectives of Ethanol Production from Sugarcane in India

6.5.1 Ethanol Blending in India

Ethanol is an easily available by-product of integrated sugar mills. Currently, ethanol is mainly engendered from molasses in India. The ethanol produced at sugar mills can later be blended with petrol and gasoline. On average, it is estimated that one tonne of sugarcane yields 110 kg of fermentable sugar from the sugarcane juice. If the juice is directly fermented into ethanol, then the average yield is around 70 liters with a sugar loss of 2% in the spent wash (Shapouri et al. 2006).

The demand for petrol in India is increasing at a steady rate due to urbanization, infrastructural development, and the resulting increase in vehicle density. Therefore, it was observed that the ethanol demand heightened for the industrial sector and other uses by 3%, and for portable use by 3.3% from 2007 to 2012 (Shinoj et al. 2011). This trend is expected to rise over the next several years. Ethanol blending is one of the most viable ways to increase domestic availability of petrol in order to limit the dependence on crude imports. Keeping this in view, India is already showing keen interest toward using ethanol as an automobile fuel. A tremendous contribution has been made by many distilleries to use surplus alcohol as a blending agent or an oxygenate in gasoline in the country.

As per policies of the Indian Government, 5% ethanol blending with petrol was targeted for October 2008 (Tiwari et al. 2015). Later, in 2009, a national policy on biofuels was formulated by Union Ministry of New & Renewable Energy (MNRE 2009). This policy set a target of 20% ethanol blending by 2017. Further, in 2013, the union government initiated the Ethanol Blended Petrol program, which made it mandatory for all oil companies to sell 5% ethanol-blended petrol. The policy was significantly focused on India's scenario to exploit the opportunities in agricultural and industrial sectors aiming at boosting biofuel usage as well as reducing the dependency on imported fossil fuel. Currently, this program is being implemented in 21 states and 4 union territories with a target of realizing 5% blending. Further, the program targets progressively increasing the blending rate to 10%. The Government of India has made significant investments in improving storage and blending infrastructure as well (Prasad et al. 2018). Figure 6.4 depicts the total available sugarcane ethanol for blending purposes after fulfilling the demands of portable, industrial, and other major uses in the Indian states. Moreover, it also provides an overview of ethanol needs of the states to fulfill various blending targets. Moreover, the ethanol demand for meeting blending targets until 2030–2031 is projected in Fig. 6.5.

At current pace, India is estimated to achieve 10% ethanol blending by 2022. The requirement of the ethanol for the country is around 3.13 billion liters (BL) in this regard. However, currently, there are no strict policy measures to divert sugarcane directly to ethanol production. Recently, the government has shown increased commitment to boost the ethanol blending at different levels in order to save money

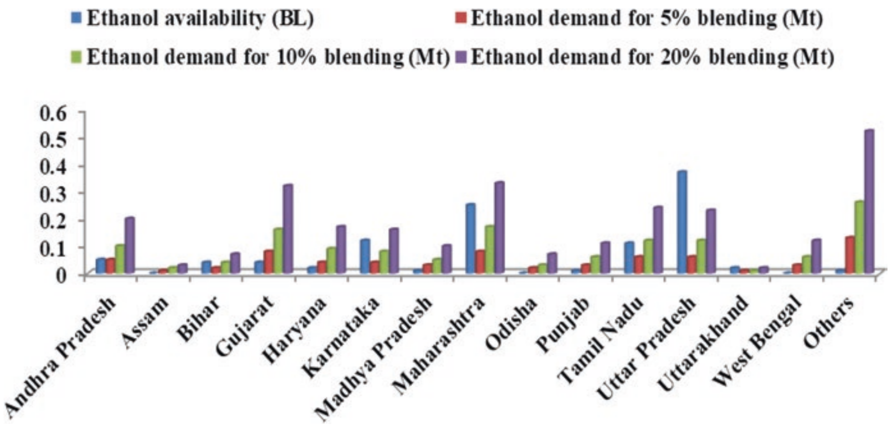


Fig. 6.4 Sugarcane ethanol availability and demand for meeting the ethanol blending targets across the different states of India [BL, billion liters; Mt., million tonnes]. (Modified from Purohit and Fischer 2014)

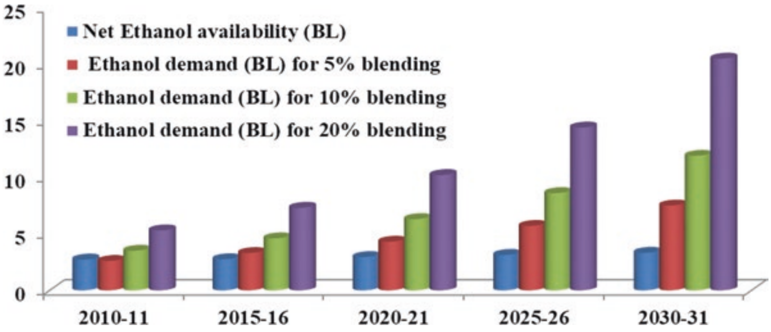


Fig. 6.5 Availability and demand of ethanol for meeting the blending targets. (Modified from Purohit and Fischer 2014)

spent on crude oil imports. Additionally, blended fuel and ethanol adoption is also being promoted at users' end as well. Design and engine modifications are planned to be introduced in the country for new vehicles which could run on 100% ethanol.

A large number of the distilleries in India are estimated to supply ethanol under the ethanol blending program. To date, India is producing over 4.5 BL of ethanol from its 330 distilleries. One hundred sixty-two distilleries in the country have capacity to distill conventional ethanol over 2.2 billion liters. India produces conventional ethanol mostly from sugar molasses—a by-product of the sugar industry—and not directly from sugarcane. Increased concentration on ethanol blending in gasoline has several benefits for farmers too including financial incentives, and more support to the agricultural sector. Additionally, ethanol blends lead to lesser pollution and reduction in import dependency. Figure 6.6 depicts the scenario of ethanol production, supply, and consumption in India (Sriram and Achur 2018).

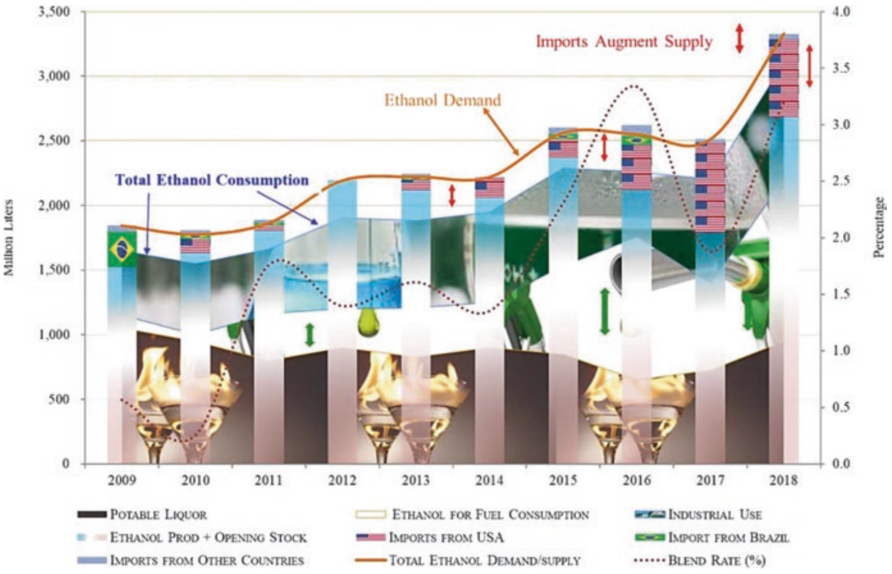


Fig. 6.6 Ethanol production, supply, and consumption in India. (Source: Wallace and Aradhey 2018)

For effective implementation of the EBP in the country, continuous supply of sugarcane feedstock (molasses, sugarcane juice, bagasse) is essential. However, sugarcane is a bumper crop that fulfills the needful demands of many sectors. In recent years, there has been a shortfall in sugarcane production due to which EBP has not been effectively implemented. Appropriate time span and research efforts would have to be employed in the automobile industry as well for manufacturing compatible engines which could use higher levels of blended fuel in future (Times of India 2018).

Various limitation and challenges are yet to be tackled for increasing ethanol-petrol blending. Strenuous efforts are necessary to increase the sugarcane yield in the country which has been stagnating at around 65–70 t ha^{-1} for years, and it is thought as if a yield plateau has been reached. Another option is to increase the number of biorefineries for ethanol engenderment. Increasing the area under sugarcane cultivation is not a viable option as it would mean land occupation of other food and staple crops which will give rise to food vs. fuel issues. Water requirements of sugarcane crop are also a limitation in this regard as approximately 20,000–30,000 cubic meters of water is needed for sugarcane cultivation per hectare. Such huge water requirements of an energy crop cast a question mark on sustainable production of the same in countries like India (Bhattacharya 2010; Shrivastava et al. 2011).

India has to either increase ethanol production by approximately three times or must opt for importing ethanol to achieve its targeted blending rates, without making a compromise to industrial, portable, and other requirements. Currently, ethanol is being produced from molasses only; however, blending requirements of the country are increasing the demands to yield ethanol directly from cane juice; nevertheless, it increases the food security concerns (Purohit and Fischer 2014).

6.5.2 Status of Electricity Cogeneration at Sugar Mills

The power sector reforms of India opened new opportunities for cogeneration. With the increasing thrust on promoting renewable energy, sugar mills' bagasse cogeneration was considered as a potential resource. India is now conventionally using bagasse as a fuel for cogeneration in all of its sugar mills. Indian Government has established policies for setting up bagasse-based cogeneration projects as well as for the purchase of generated power. Such policies urged the sugar mills to set up high-efficiency cogeneration systems to generate surplus power for sale to the national grid.

Various valuable by-products such as molasses, bagasse, and syrup are generated during the sugar production process. Bagasse is lignocellulosic fiber that remains after the crushing of sugarcane. It has good calorific value and can be burnt as fuel. The sugar industry is using bagasse for electricity and steam in the milling operations. Bagasse is easily burnt in boilers for steam production which is further utilized in turbine generator for electricity production. The surplus bioelectricity thus yielded is available for sale to the national grid. Ministry of New and Renewable Energy (MNRE) has been providing incentives for surplus bioelectricity cogeneration at the sugar mills. The agency targets promotion of biomass-based cogeneration to yield electricity and encourages its sale.

A total of 213 sugar mills have already been supported for installing optimal cogeneration plants, which count for a total capacity of approximately 2332 MW. Uttar Pradesh is leading with its cogeneration-based electricity production capacity of 711 MW through 53 projects. Moreover, Maharashtra have a capacity of 581 MW electricity production from its 65 projects, whereas Karnataka, and Tamil Nadu have capacity of 404 MW (32 projects), and 327 MW (26 projects), respectively. Furthermore, 37 projects are installed in other states as well, which have a capacity to produce up to 310 MW of electricity. Nearly four million units of electricity per megawatt of bagasse cogeneration-based plant are generated per annum, and the price of electricity ranges from INR 3.50 to 5.50 per unit (Shailesh 2013).

6.5.3 National Policies Regarding Ethanol Blending in India

Numerous policies were launched for ethanol blending to fulfill the Indian blending targets and biofuels adoption. Recently, the Union Cabinet of India has approved National Policy 2018 on Biofuels so that the biofuel production within the country may be promoted. The objective of the National Policy on Biofuels has been to foster and strengthen the Ethanol Blending Petrol Program (EBPP) in the country. A timeline of national policies and developments for ethanol blending is presented in Table 6.5.

Table 6.5 Timeline of national policies for ethanol blending in India

Year	Act/policy	Features
1948	Power Alcohol Act	Blending of ethanol from molasses (alcohol) with petrol was emphasized for reducing the sugar prices and limiting waste production and the dependence on imported petrol (Basavaraj et al. 2012)
2001	Pilot projects (at Miraj, Manmad, and Bareilly)	Three pilot projects were launched: two in Maharashtra (Miraj and Manmad) and one in Uttar Pradesh (Bareilly). The purpose of the plants was to analyze the feasibility of ethanol blending with petrol
2003	EBP Program	The Ethanol Blending Program was initiated to target the production and sale of 5% ethanol-blended petrol in nine states and four union territories in the country (Ray et al. 2012)
2006	Resumption of EBP	The EBP was extended to 11 more states of the country (Ray et al. 2012)
2009	National Biofuel Policy	Five percent blending was made mandatory in India A target of 20% blending by 2017 was set both for biodiesel and ethanol (Ray et al. 2012)
2010	Provisional ad-hoc procurement price of ethanol	An ad-hoc provisional procurement price of INR 27 per liter of ethanol was set by the GoI
2012	Cabinet Committee on Economic Affairs (CCEA)	The cabinet committee decided that 5% ethanol blending should be mandatory and implemented all across the country. Moreover, it was also proposed that ethanol's purchase price would be decided between Oil Marketing Companies (OMCs) and the suppliers (Lagos and Aradhey 2013)
2014	Cabinet Committee on Economic Affairs	Ethanol prices were fixed based on the distance between the supplying mill/distillery and OMC
2015	–	Central excise duty of 12.36% was exempted on ethanol supplied specifically for blending purposes
2016	Cabinet Committee on Economic Affairs	The concession on excise duty was eliminated (Mukherjee 2016) The administered price of ethanol was adjusted to INR 39 per liter for the period 2016–2017

Biofuel production in India is aimed at playing important role in economy and contributes toward Indian Government's initiatives such as Make in India, Skill Development, and Swachh Bharat Abhiyan. Biofuel blending also deals with achieving the ambitious goals of doubling the farmers' income, employment generation, import reduction, and waste to wealth concept.

6.6 Future Perspectives of Cane Ethanol Production in India

It is evident from Indian Government's policies that the role of sugarcane crop in biofuels sector of the country is anticipated to increase even more. Currently, in spite of being second largest producer of this crop, even 5% blending targets of India are not being fulfilled by sugarcane because of high demand of ethanol in other sectors such as liquor industry. The government is targeting even higher blending rates in order to reduce GHG emissions, promote agriculture, generate employment opportunities, and limit the oil import burdens. Thus, sugarcane production must be increased in the country either by increasing its per unit area yields or expanding its production to areas where sustainability concerns are not high. Another option is the production of ethanol from sugarcane juice directly, which would, however, increase the concerns about sugar prices.

A tremendous potential exists for sugarcane crop in India as a source of ethanol, sugar, and bio-products. In order to make ethanol production more cost-effective, installation of state-of-the-art techniques like molecular sieve technology for creating anhydrous ethanol can help. Enforcement of a stable blending program would encourage the investments, benefiting sugarcane farmers and the industry. Biotechnology applications can also help in enhancing the sugar contents of the sugarcane, leading to development of high-recovery cane genotypes. Moreover, biotechnological applications can play significant role in reducing the ethanol production costs as well.

In India, efforts should also focus on development of cost-effective processes for ethanol production from sugarcane by using cutting-edge technologies like the use of membranes and genetically modified microbes, improved key enzymes, elite strains of yeast for fermentation, and optimized fermentation processes. Several policy problems associated at national and state level have already been mentioned and an action set up for bioethanol engenderment, and its phase-wise expansion is counseled in the chapter. In conclusion, the sugarcane industry is predicted to make even important contributions to meet India’s energy needs by supplying renewable, clean, nontoxic, and eco-friendly fuel.

6.7 Conclusion

India is second largest sugarcane grower, and one of the biggest producers of sugar and ethanol. However, most of the ethanol is consumed for applications in liquor and chemical industries. The surplus ethanol can hardly fulfill the present 5% blending demands of the nation. This blending level is obligatory and enforced in many of the states. Therefore, India is needing huge supplies of ethanol for meeting its blending goals, either through its major indigenous source, i.e., sugarcane, or by imports. The demands will be even higher once the blending program is enforced nationwide or if the blending ratio is inflated—as the government is already planning to enhance up to 20%. Sugarcane, being the main source of ethanol for the country, is playing significant role in this regard, and its position is expected to strengthen even more in the coming years.

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Chapter 7
Sugarcane Biofuels Production in China

Yun-Hai Lu and Yan-Qing Yang

7.1 The General Situation of Sugarcane Cultivation in China

Sugarcane is an economically important crop in China. It was traditionally planted (before 1985) in the southern regions of China, such as Guangdong, Guangxi, Yunnan, Hainan, Fujian, Taiwan, Jiangxi, Sichuan, Hunan, Zhejiang, Guizhou, and Hubei. Along with the rapid economic development in the country, the production of sugarcane has been declining in the eastern coastal regions such as Fujian and Guangdong but expanding in the western inland regions such as Guangxi and Yunnan (Li et al. 2017; Wu et al. 2017). Sugarcane is generally planted from December to March and harvested once every year after a period of 10–14 months of growth, with an average of two ratoon crops for each planting. While over 80% of the sugarcane land preparation is now done with machines, the harvesting is still essentially done manually in most of the sugarcane-growing areas (Peng et al. 2014). In 2018, the proportions of newly planted first ratoon, second ratoon, third ratoon, and fourth or more ratoon sugarcane crops were 39%, 32.4%, 18.9%, 7.6%, and 2.1%, respectively (Guangxi Sugar Network 2018). The report from China Industry Information Network (2017a) showed that the sugarcane planting area varied from 1.378 to 1.816 million hectares in China (mainland) during the period of 2006–2016 (Fig. 7.1), whereas the sugarcane production varied from 97.9 to 128.20 million tons for the same period (Fig. 7.2). In 2016, the sugarcane-planted area in the four main sugarcane-growing provinces, Guangxi, Yunnan, Guangdong, and Hainan, was 1.0815, 0.3397, 0.1675, and 0.0619 million hectares, respectively (China Report Network 2017). These four provinces accounted for over 90% of the total sugarcane planting area in China, of which Guangxi contributed by 62.28% (Fig. 7.3).

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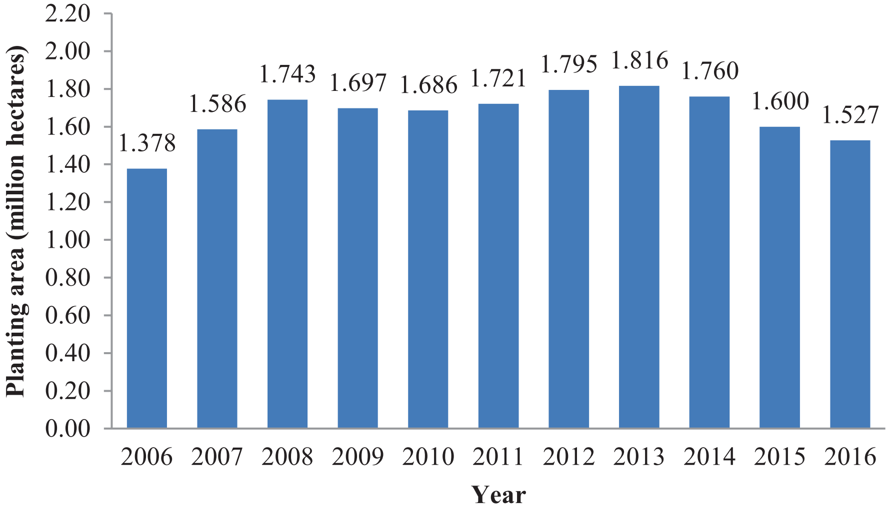

Fig. 7.1 Evolution of sugarcane planting area (million hectares) during 2006–2016 in China mainland (China Industry Information Network 2017a)

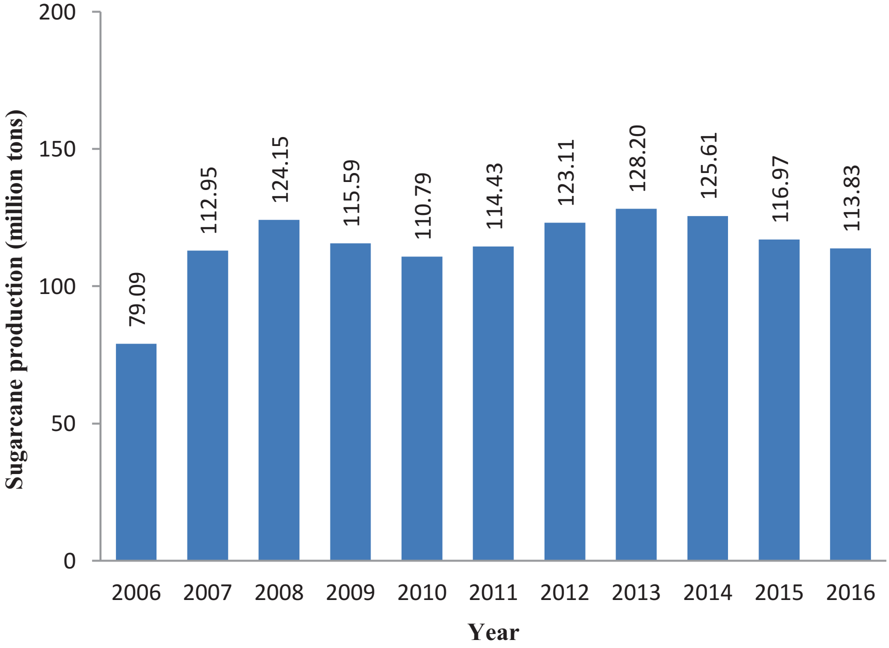

Fig. 7.2 Evolution of sugarcane production (million tons) during 2006–2016 in China mainland (China Industry Information Network 2017a)

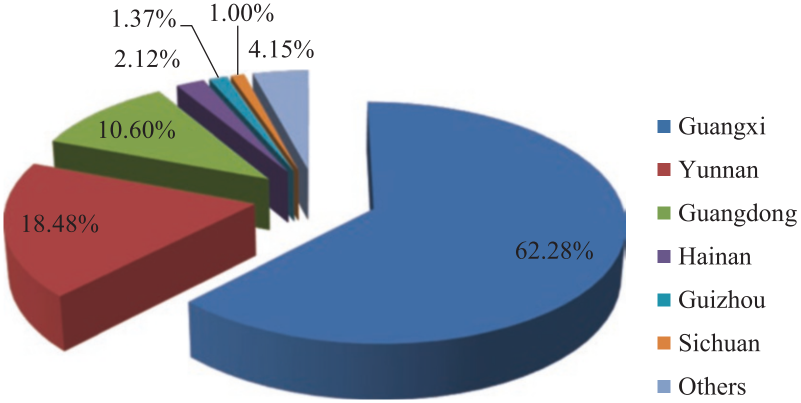

Fig. 7.3 Proportion (%) of sugarcane planting area in different regions of China mainland in 2016 (China Industry Information Network 2017a)

Since many years, most of the cultivated sugarcane varieties have been limited to a few ROC series genotypes that were introduced from Taiwan (Li and Deng 2011). In 2011, the ROC serial varieties occupied over 80% of the total sugarcane planting area in China, and a single variety named ROC22 (a hybrid variety introduced in 1998 by Guangxi Academy of Agricultural Sciences) occupied over 60% of the total sugarcane planting area in China. As per 2018, the ten most cultivated sugarcane varieties were ROC22 (448,760 ha), GL05-136 (145,087 ha), GT42 (111,960 ha), YT93-159 (77,113 ha), ROC25 (29,093 ha), YT00-236 (19,127 ha), YT94-128 (15,987 ha), YT86-368 (15,720 ha), YT55 (14,727 ha), and ROC79-29 (13,427 ha), which occupied nearly 80% of the total sugarcane planting area in the country (Yunnan Sugar Network 2018). ROC22, alone, occupied as high as 39.89% (compared to 55.54% in 2016) of the total sugarcane planting area in China.

7.2 The Sugar Production and Sugar Industry in China

China is the third largest sugar producer following Brazil and India, and second largest sugar consumer (following India) in the world (China Industry Information Network 2017b). China produces both cane sugar and beet sugar. The annual sugar production varied between 9.49 and 16.43 million tons during the period 2006–2017 (Fig. 7.4). The cane sugar accounts for over 90% of the China's total sugar production until recent years (China Report Network 2017; Peng et al. 2014; Wei et al. 2015).

Figure 7.5 shows the 2017 sugar production in different regions of China. Guangxi alone produced 9.3596 million tons of sugar and accounted for 63.94% of the total sugar production in China in 2017. Yunnan occupied the second position and produced 2.2713 million tons that shared 15.52% of the total sugar production

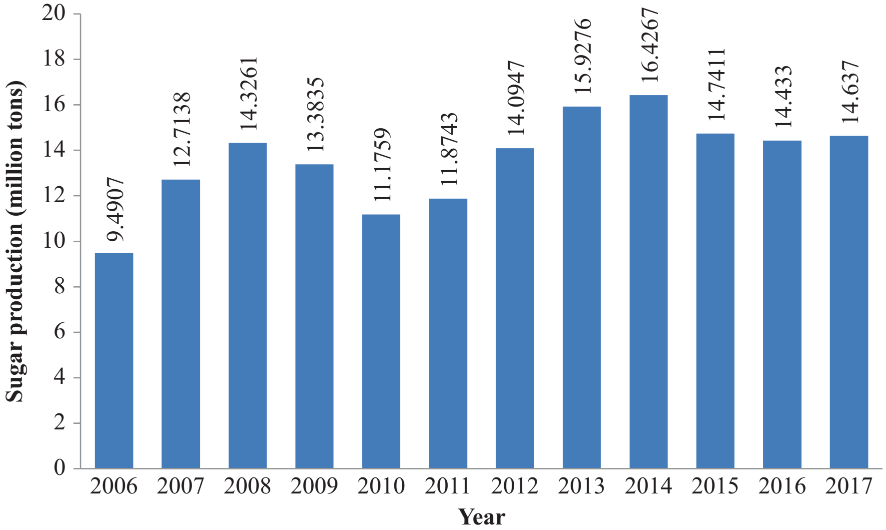

Fig. 7.4 Evolution of sugar production (million tons) during 2006–2016 in China mainland (China Research Network 2018; China Commercial Information Network 2018)

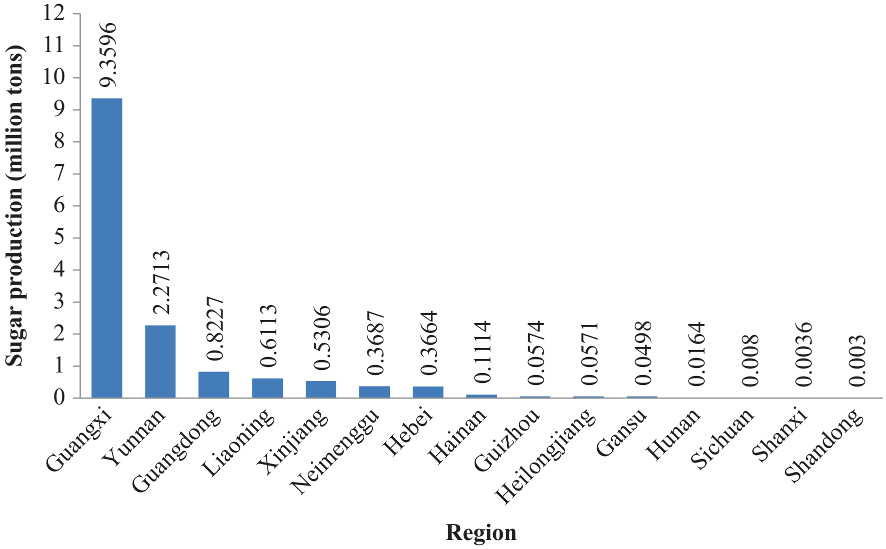

Fig. 7.5 Sugar production (million tons) in different regions of China mainland in 2017 (China Commercial Information Network 2018)

in the same year. Following Yunnan, Guangdong occupied the third position and yielded 0.8227 million tons that accounted for = 5.62% of the total 2017 sugar production in China. The sugarcane-growing regions, including Guangxi, Yunnan, Guangdong, Hainan, Guizhou, and Sichuan, together produced a total of 12.63 million tons of cane sugar and hence contributed 86.29% of the total sugar engendered in China. Other regions including Liaoning, Xinjiang, Neimenggu, Hebei, Heilongjiang, Gansu, Hunan, Shanxi, and Shandong together produced 2.01 million tons of beet sugar and accounted for 13.71% of the total 2017 sugar produced in China.

Since 2004, China has been importing sugar from other countries every year (except 2007/2008) due to rapidly increasing domestic sugar consumption than the production (Peng et al. 2014). In 2013/2014, 2014/2015, 2015/2016, 2016/2017, and 2017/2018, the total sugar imports were 4.02, 4.81, 3.73, 2.27, and 2.50 million tons, respectively, while the total sugar exports were 0.04, 0.04, 0.15, 0.07, and 0.07 million tons, respectively (China Industry Information Network 2018a). In 2017/2018, the sugar price varied between 5800 and 6400 RMB tonne−^{1}. The average sugar price was observed to decline by 7% against the sugar price in 2016/2017. On the other hand, minimum cost for 1 ton of sugarcane was 500 RMB, while average cost for producing 1 ton of sugar from (~8 tons of) sugarcane was 5700 RMB (China Industry Information Network 2018a). For beet sugar, the cost for 1 ton of sugar production was 540 RMB, and the average cost for producing 1 ton of sugar from ~8.33 tons of beet was 4700 RMB (Hua Xia Chem Network 2017). This indicated higher profit margins and cost-benefit ratio for beet sugar as compared to the cane sugar which explains the increasing trend in sugar beet planting in the northern regions of China.

Yang (2016) analyzed the challenges being faced by China's sugar industry. Sugarcane farms in China are generally managed on a small scale (Peng et al. 2014). The average area per farm is estimated to be 0.27 hectares. However, some company-owned large-scale farms also exist, such as Guangdong Zhanjing State Farms Bureau which possesses 19 sugarcane farms with an average area of about 1400 hectares each. In 2009/2010, a total of 238 sugar mills (37 state-owned, 11 foreign-owned, and 190 private-owned) were in operation, with an average throughput capacity of about 4000 tons of cane stalks per day (compared to 8000 tons in Brazil and 10,000 tons in Australia). Of these 238 sugar mills, 71 have a crushing capacity over 5000 tons per day, with the biggest capacity of about 27,000 tons per day of Funan sugar mill of East Asia Sugar Industry Group. The largest sugar company of China, named Guangxi Nanhua Sugar Group, produced about 1.68 million tons of sugar (cane sugar + beet sugar) in 2010/2011 sugar pressing season from its 38 sugar mills.

Table 7.1 shows the general situation of Chinese sugar mills from 2011 until 2016. It has been noted that the economic situation is not favorable for many of the Chinese sugar mills as more than a third of the mills have been in deficit since 2012. In 2016, there were a total of 308 sugar mills in China; the number of mills being above the designated figure for the country. The sugar industry had total assets of 208.469 billion, output value of 118.825 billion, total sales revenue of 109.976

Table 7.1 General situation of Chinese sugar mills during 2011–2016

Year	Number of sugar mills	Number of sugar mills in deficit	Average loss per sugar mill in deficit (million RMB)	Total assets (billion RMB)	Total output (billion RMB)	Total sales revenue (billion RMB)	Total profit (billion RMB)
2011	282	37	13.000	110.425	111.033	100.564	13.285
2012	290	90	17.688	139.126	119.304	109.165	6.956
2013	304	127	23.105	154.568	126.894	118.130	5.266
2014	311	171	33.911	173.910	121.950	112.176	1.841
2015	297	155	14.083	193.059	110.276	100.366	2.845
2016	308	134	14.836	208.469	118.825	109.976	3.387

China Industry Information Network (2017c)

billion, and total profit of 3.387 billion RMB in the year 2016 (China Industry Information Network 2017c). One hundred and thirty four of the 308 sugar mills were in deficit, with an average loss of 14.836 million RMB per sugar mill.

Among the top 50 sugar mills (by production), 37 are located in Guangxi province (Guangxi Sugar Network 2016), whereas the total number of mills in Guangxi province is 103 (Tao Dou Network 2016). In 2017/2018 sugarcane pressing season (from 15 November 2017 to 26 April 2018), 91 sugarcane mills were operational in Guangxi province with a total throughput of 50.80 million tons of cane stalks for the mentioned period. The mills, on average, can crush 0.63 million tons of cane stalks per day and 6923 tons per day per mill (Liang 2018).

7.3 Bioenergy Production in China

The development of biofuels in China has been previously reported and reviewed (Chang et al. 2012; Chen et al. 2016; Hao et al. 2018; Li et al. 2015; Qiu et al. 2012; Ren and Dou 2018; Xu et al. 2016; Wang et al. 2009; Zhong et al. 2010). Figure 7.6 shows the evolution of China's biofuels (fuel ethanol and biodiesel) production since 2012. China introduced its biofuel production program in the 1990s, when it became a net crude oil importing country. The program was initiated by the country realizing its energy needs, challenges associated with heavy dependence on foreign oil, and the issues related to environmental pollution expected from the dramatic increase in the number of automobiles along with the rapid industrial development (Zhong et al. 2010).

During China's tenth five-year planning period (2001–2005), China commenced a nationwide fuel ethanol demonstration program. In 2002, two state-owned industrial-scale fuel ethanol plants were established for biofuel production using stale maize and wheat as feedstocks. Tianguan Fuel Ethanol Co. Ltd. (in Henan province), with a production capacity of 300,000 tons per year, and Helongjiang COFCO Bio-energy (Zhaodong) Co. Ltd., having a capacity of

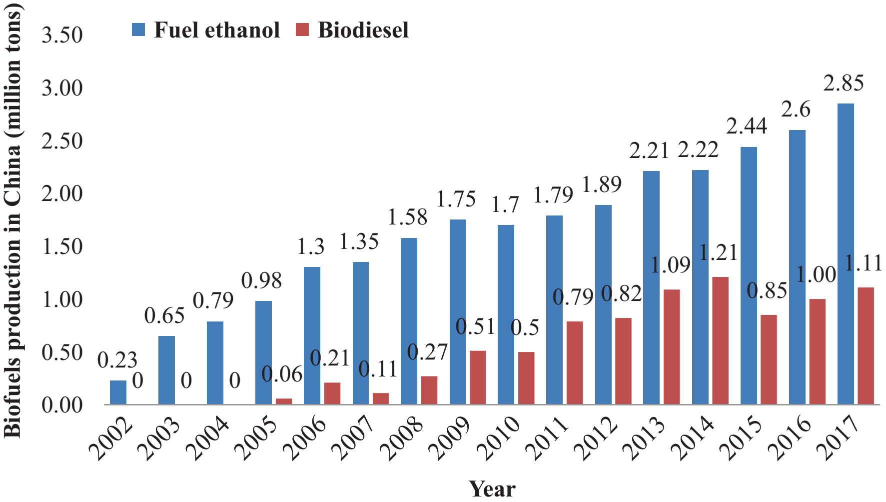

Fig. 7.6 Evolution of China's biofuels production during 2002–2017 (China Industry Information Network 2018b; China Report Network 2018; Hao et al. 2018)

100,000 tons per year, were started to provide fuel ethanol to five Chinese cities including Zhengzhou, Luoyang, Nanyang, Haerbin, and Zhaodong (Hao et al. 2018; Liu 2006). In 2004, the demonstration program was expanded through two more companies constructed in Jilin and Anhui provinces. Jilin Fuel Ethanol Co. Ltd. with production capacity of 300,000 tons per year and Anhui BBCA Biochemical Fuel Alcohol Co. Ltd. having ethanol production capacity of 320,000 tons per year expanded the test areas to nine demonstration districts (Heilongjiang, Jilin, Liaoning, Henan, Anhui, Hubei, Shandong, Hebei, and Jiangsu) at provincial and urban levels (Hao et al. 2018; Liu 2006). By the end of 2005, the consumption of E10 gasoline (with 10% of ethanol) in the nine demonstration provinces was about ten million tons and accounted for approximately 20% of the national gasoline consumption in China. A total sum of about 2 billion RMB were provided by the Chinese government as subsidy for the fuel ethanol production and extension during 2001–2005 (Liu 2006).

Driven by the potential profit from fuel ethanol engenderment, many local governments and private organizations initiated new fuel ethanol projects during the same period. The consumption of feedstock corn increased significantly from 12.5 million tons in 2001 to 23.0 million tons in 2005 (Hao et al. 2018). By the year 2006, the total amount of investment in fuel ethanol industry in China was over 10 billion RMB and this sector had a production capacity of over ten million tons per year (Hao et al. 2018; Ren and Dou 2018). To avoid the excessive corn consumption and its negative impact on food security, the government strengthened the entry regulations to halt the establishment of new food-based fuel ethanol projects and restrict the expansion of existing fuel ethanol programs (Hao et al. 2018). Instead, the government promoted the development of nonfood-based biofuels.

In 2007, a state-owned cassava-based fuel ethanol company, named Guangxi COFCO Bio-energy Co. Ltd., was initiated in Guangxi province (Ren and Dou 2018). The plant had a production capacity of 200,000 tons per year fuel ethanol production. This project was followed by the establishment of four other cassava-based fuel ethanol production projects. The projects included SDIC Guangdong Bio-energy Co. Ltd., Hainan Yedao Shihua New Energy Co. Ltd., Zhejiang Zhoushan Biofuel Ethanol Co. Ltd., and Jiangxi Yufan Bioenergy Co. Ltd., with production capacity of 150,000, 100,000, 300,000, and 100,000 tons per year, respectively (Hao et al. 2018). In addition, several cellulosic ethanol projects were also established, e.g., Shandong Longlive Ethanol Technology Co. Ltd. was initiated to engender ethanol from corncob, with an initial capacity of 3000 tons per year (Qiu et al. 2012; Zhong et al. 2010). Due to the relative success of pilot projects, some food-based fuel ethanol companies also began to produce cellulosic ethanol, such as Tianguan Group Co. Ltd. aimed at utilizing straw as feedstock for an annual production capacity of 3000 tons of fuel ethanol (Zhong et al. 2010). Moreover, CNPC also cooperated with COFCO (China National Cereals, Oils & Foodstuffs Import and Export Corporation) to jointly construct 20 cellulosic ethanol plants across China to target at a total production capacity of 2,000,000 tons per year ethanol (Qiu et al. 2012). However, the production of cellulosic ethanol has been, and is still, very low until now due to technical and cost issues (Hao et al. 2018).

In order to limit the excessive consumption of corn and maize, and to promote the development of nonfood-based fuel ethanol, the Chinese government reduced the subsidies to food-based fuel ethanol units (Fig. 7.7), completely eliminating such subsidies by 2016 (China Industry Information Network 2017d). Following

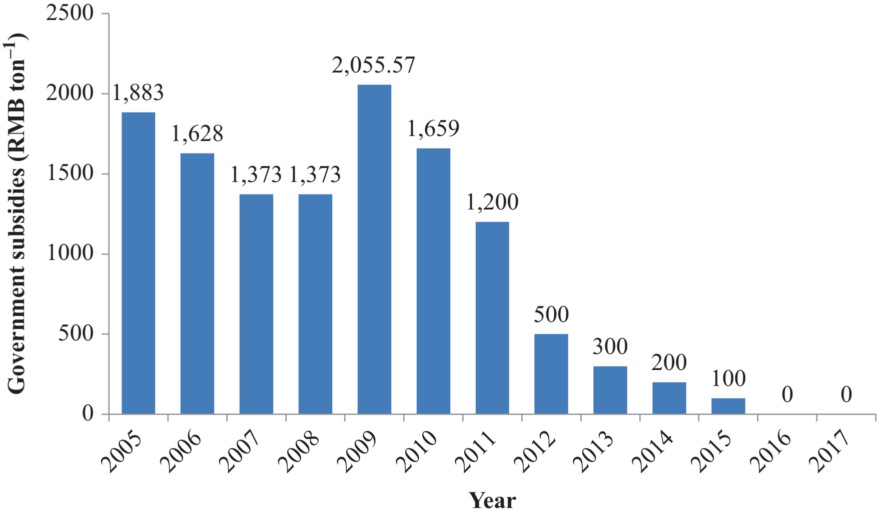

Fig. 7.7 Evolution of the Chinese government's subsidies to food-based fuel ethanol production during 2005–2017 (China Industry Information Network 2017d)

these policy shifts, the National Engineering Research Center for Non-food Biorefinery was approved by the Ministry of Science and Technology of China and established in Guangxi Academy of Sciences, Nanning, in 2009 (Guangxi News 2009). The mission of the center was to provide solutions to the technical and economic issues of the industrial production of biofuels from cassava, sugarcane, and sweet sorghum in the country.

Table 7.2 presents a list of China's major fuel ethanol producing companies in 2017, with their location, feedstock type, and production capacity (China Report Network 2018). Among these, four are food-based utilizing corn or wheat as feedstock (first-generation biofuel), two are cassava-based (1.5-generation biofuel), and the remaining four are cellulosic feedstock-based (second-generation biofuel). In 2017, China produced a total of 2.85 million tons of fuel ethanol, compared to 2.6 million tons in 2016 (Fig. 7.6).

In 2016, the use of E10 gasoline was expanded to over 12 provinces in China. These included Heilongjiang, Henan, Jilin, Liaoning, Anhui, Guangxi, Hebei, Shandong, Jiangsu, Neimenggu, Hubei, and Guangdong provinces (China Industry Information Network 2017d). According to the government's planning, the use of

Table 7.2 China's major fuel ethanol producing companies in 2017

Company	Location	Feedstock biomass	Capacity/year (tons)
Tianguan Fuel Ethanol Co. Ltd	Nanyang, Henan	Corn, wheat, straw	700,000
Jilin Fuel Ethanol Co. Ltd	Jilin, Jilin	Corn	600,000
Anhui BBCA Biochemical Fuel Alcohol Co. Ltd	Bengbu, Anhui	Corn	440,000
COFCO Bio-energy (Zhaodong) Co. Ltd	Zhaodong, Heilongjiang	Corn	250,000
Guangxi COFCO Bio-energy Co. Ltd	Beihai, Guangxi	Cassava	200,000
Zhongxing Energy Co. Ltd	Neimemggu	Sweet sorghum	30,000
Shandong Longlive Ethanol Technology Co. Ltd	Dezhou, Shandong	Corncob	50,000
SDIC Guangdong Bio-energy Co. Ltd	Zhanjiang, Guangdong	Cassava	150,000
Liaoyuan Jufeng Biochemical Technology Co. Ltd	Liaoyuan, Jilin	Corn	50,000
Jinan Shengquan Group Co. Ltd	Jinan, Shandong	Corncob, straw	20,000
Shandong Zesheng Biotechnology Co. Ltd	Dongping, Shandong	Straw	20,000
Yanchang-Zhongke (Dalian) Energy Technology Co. Ltd.	Dalian, Liaoning	Coal	100,000
Zhongrong Technology Co. Ltd	Qianan, Hebei	Coal	100,000
Total			2,710,000

China Report Network (2018)

E10 gasoline will be generalized to all regions of China mainland by 2020, and an annual production of 15 million tons of fuel ethanol will be targeted to meet an annual consumption of 150 million tons of gasoline for automobiles (China Report Network 2018). These figures indicate that China has huge market potential for fuel ethanol. As per 2015, the country is the third largest producer of fuel ethanol in the world but accounts for only 3% of the total global fuel ethanol production following the USA and Brazil, which have biofuels' share of 58 and 28%, respectively (China Industry Information Network 2017e).

China's biodiesel has been produced by private companies mostly (Chang et al. 2012; Xu et al. 2016). In comparison with fuel ethanol, biodiesel projects are smaller and more dispersed and have lower utilization rates due to shortage and instability of feedstock availability (Fig. 7.6). Waste oil is the major feedstock for country's biodiesel production, although various crop-based oils are also being tested as feedstocks (Chang et al. 2012; Hao et al. 2018; Qiu et al. 2012). Three projects using seeds of energy trees such as *Jatropha curcas* as feedstock were approved in 2008 by the National Development and Reform Commission of China as pilot demonstrations with a collective capacity of 170,000 tons per year (Chang et al. 2012; Hao et al. 2018; Yang and Guo 2009). The plants were then established later in Hainan, Sichuan, and Guizhou by China National offshore Oil Corporation (CNOOC), China National Petroleum Corporation (CNPC), and China Petroleum and Chemical Corporation (SINOPEC). In recent years, the development of biodiesel experienced a rapid growth in China (China Industry Information Network 2018b).

In 2017, 200 companies were involved in biodiesel production in China, and the total annual biodiesel production was 1.1 million tons in the country (Fig. 7.6). Among these, over 40 corporations have production capacity of more than 5000 tons per year. Biodiesel is mainly used in the form of B5 (95% diesel +5% biodiesel) for road vehicles in China. In 2016, China has consumed a total of 165 million tons of diesel, indicating a tremendous potential for the development of biodiesel in China in future (China Industry Information Network 2018b).

7.4 Current Status of Bioenergy Production from Sugarcane in China

The potential, advantages, and prospects of sugarcane as a bioenergy crop in China have been explored by various researchers (Cai and Wu 2006; Chen 2009; Lan 2007; Li and Yu 2007; Li et al. 2004; Li et al. 2007a, b; Li et al. 2014; Liu and Li 2015; Qin and Deng 2011; Tan 2004; Xu and Chen 2009; Zhang and Chen 2002; Zhao et al. 2010). To meet the increasing demands for both sugar and bioenergy, China adopted the content of "sugarcane breeding for high radiation use efficiency and high biomass" in the National Key Technologies R&D Program of the ninth five-year plan (1996–2000) (Peng et al. 2014). Since then, a series of sugarcane varieties with high sugar content (for production of fuel ethanol from molasses) and increased biomass (for production of electricity and cellulosic fuel ethanol) have been successfully developed by sugarcane breeders. FN90-6652, FN93-3406, FN95-1630, and FN98-0502 developed by Fujian Agriculture and Forestry University, Fujian, have the biomass yields as high as 150–180 tons per hectare and a fermentable sugar content superior by 25%. Moreover, YT93-159, YT94-128, and YT00-236 were developed by Guangzhou Sugarcane Industry Research Institute, Guangdong; GT22, GT33, and GT39 by Guangxi Academy of Agricultural Sciences; YZ94-375 and YZ99-155 by Yunnan Academy of Agricultural Sciences; and CZ23 by Sichuan Sugar Crops Industry Research Institute keeping in view the same targets (Mao et al. 2014).

Recently, Peng et al. (2014) reviewed the overall situation of bioenergy production from sugarcane in China. According to his work, sugarcane is mainly being used for producing sugar to meet the huge demand for this product in the country. However, other by-products such as electricity, ethanol, steam, paper, and boards are also being produced. According to the report of Zhong et al. (2010), China's fuel ethanol production reached 1.5 million tons per year in 2008, of which about 55% was produced from corn and cereals, 33% from tuberous crops, and 12% from sugarcane molasses.

All of the large sugar mills in China have resources to produce ethanol from molasses; nevertheless, sugarcane is not extensively used for bioenergy production on large scale due to low competitiveness (Chen 2009; Peng et al. 2014). It is perceived by the mills that sugar production from sugarcane is more profitable than the fuel ethanol production using first-generation technology which competes with sugar engenderment. Competitiveness of other ethanol applications also does not favor fuel ethanol production. For example, about 600,000 tons ethanol was produced from molasses in 2010, but all of it was designated for beverages. Sugar sector of China also has good potential for cogeneration of electricity; however, most of it is ultimately destined for mills' own uses, and contribution toward national grid remains low. Three million MWhe of electricity was generated from bagasse in 2013, but 75–80% of it was reused for internal uses of the units (Peng et al. 2014).

In sugarcane pressing season of 2014–2015, sugar mills from Yunnan province produced 2,306,800 tons of sugar, 127,300 tons of ethanol, and 184,300 tons of biomass fuel. Moreover, these mills also produced 11,500 tons of paper, 420,000 tons of compound fertilizers, and 35,000 tons of edible yeasts (Deng and Zhang 2016). Li (2017) reported that the sugar mills from Guangxi province produced 9,370,000 tons of sugar and 1,800,000 tons of molasses in their best crushing year. In 2016, the National Environmental Protection Agency of China only authorized the plants having annual production capacity superior than 15,000 tons to operate. Hence, 18 cane ethanol plants in Guangxi province were meant to produce ethanol from molasses; however, only five of them operated in 2016 due to the low price of ethanol in the country (Li 2017).

Sugarcane bagasse is the main by-product of sugar industry which can be transformed into high value-added products (Lan 2007; Liang et al. 2003; Tu et al. 2006; Wang et al. 2010; Yu and Mo 2013). Li et al. (2017) analyzed the current status of sugarcane bagasse usage in China, including the production of electricity through cogeneration, biogas, and fuel ethanol. According to their results, the four main Chinese sugarcane-growing provinces, i.e., Guangxi, Yunnan, Guangdong, and Hainan, engendered 16,250,000, 5,625,000, 3,700,000, and 625,000 tons of bagasse, respectively, in 2015. Thus, total bagasse production in these four provinces stood at 26,200,000 tons. However, about 75–80% of the sugarcane bagasse was employed for generation of steam and electricity for mills' internal processing uses through direct burning (Niu 2014).

In order to make efficient use of cane bagasse in energy production, about eight billion RMB were invested during 2012–2016, to help the 103 sugar mills in Guangxi province for cogeneration of electricity (Li et al. 2017). Such investments can make the sugar mills self-sufficient regarding their electric power needs and can also result in provision of about 4.5 million MWhe of electricity to the external electricity grids (Qianzhan Network 2012). In Guangdong province, the Zhanjiang Biomass Power Plant—the world's largest biomass power plant—was established in 2011 (Finance China 2017). The plant mainly consumes the bark or branches of eucalyptus tree as well as sugarcane bagasse and cogenerates over 650 MWhe of electricity per year to the public electricity grids. On the other hand, the biomass power generation can help the plant save more than 280,000 tons of coal, reduce carbon dioxide emissions by 480,000 tons per year, and achieve zero emission of sulfur dioxide from the unit (Finance China 2017). Although, the rate of bagasse's utilization for electricity production is actually quite good in China, the generated commercial value is low. Therefore, the production of electricity is considered a short-term option before other more efficient transformation technologies are developed (Li et al. 2017).

Figure 7.8 shows the evolution of China's biomass-based electricity production (including agricultural and forestry biomass, life garbage, and biogas) during 2010–2017 (China Industry Information Network 2017f). We can observe a rapid development of China's biomass-based electricity production industry in recent years. In 2017, a total of 79.45 million MWhe of electricity were produced from biomass, of which 39.73 (50%) were generated through direct burning of agricultural and forestry biomass, 37.52 (47.22%) through burning of life garbage, and 2.20 (2.77%) through burning biogas (China Industry Information Network 2017f). In fact, China began to produce electricity from biomass in an industrial scale only since 2006, with sugarcane bagasse as the main biomass resource (account for 77%) for the initiation. According to China's thirteenth five-year (2016–2020) plan, an annual production of 90 million MWhe of biomass-based electricity should be achieved by 2020 (China Industry Information Network 2017g).

Following first-generation ethanol production and electricity cogeneration, sugarcane can also serve provision of second-generation fuel ethanol. However, production of this type of fuel ethanol from bagasse is in experimental stages yet and limited mainly by cost and low efficiency of the pretreatment options for bagasse and lignocellulosic materials (Liu et al. 2017; Peng et al. 2014).

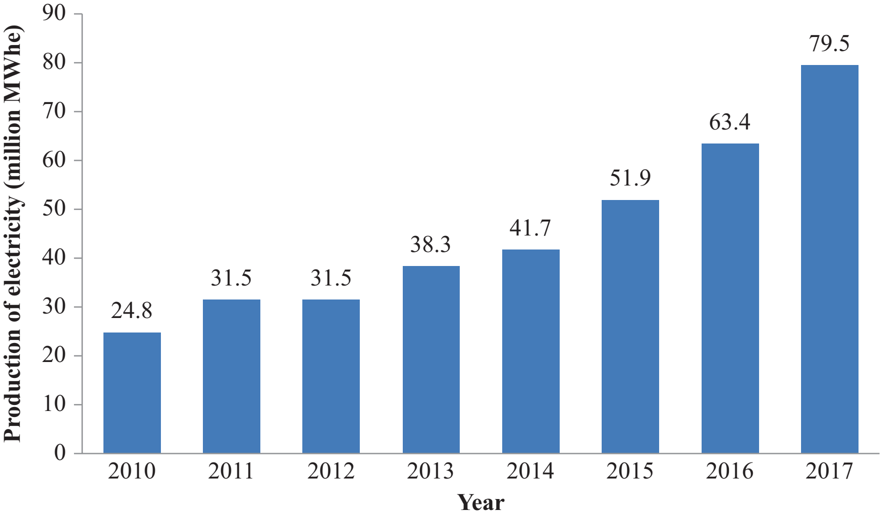

Fig. 7.8 Evolution of China's biomass-based electricity production (including agricultural and forestry biomass, life garbage, and biogas) during 2010–2017 (China Industry Information Network 2017f)

7.5 Future Perspectives of Sugarcane Fuels in China

Sugarcane has been widely accepted as a promising energy crop in China (Chen 2009; Li et al. 2007b). The climate and soil conditions in southern China are very suitable for sugarcane growing, and an annual biomass production of over 280 tons per hectare can be expected in these regions (Li et al. 2007b). With the rapid development of biomass-based bioenergy industry in the country, the sugarcane planting area can be doubled and reaches 2.5 million hectares in southern China (Li et al. 2007b; Zhang and Chen 2002). Although the production of first-generation fuel ethanol from sugarcane is actually not competitive enough with regard to its cost, the successful experiences from Brazil will continue to bring optimism to the sector in China (Chen 2009; Lopes et al. 2016; Zhao et al. 2010). Vigorous research efforts have resulted in significant achievements regarding pretreatment technologies which will help the production of second-generation fuel ethanol from sugarcane bagasse (Khan et al. 2017; Li et al. 2010; Li et al. 2018; Ye et al. 2018). The industrial production of fuel ethanol from sugarcane bagasse can benefit from the successful experiences of Shandong Longlive Ethanol Technology Co. Ltd. (Lan 2007). Moreover, progress in sugarcane molecular breeding, transgenics, and genome editing is expected to enhance sugarcane's first- and second-generation ethanol production capacity in China and also contribute toward making the digestion of lignocellulosic contents highly cost-effective (Du et al. 2018; Kandel et al. 2018; Lam et al. 2009; Lu and Mosier 2008; Xie and Peng 2011).

7.6 Conclusion

Biofuels are a promising solution to the energy shortage and environmental pollution issues caused by the rapid economic and industrial development of China. Sugarcane is an economically important crop and a promising nonfood energy source in southern China. China's fuel ethanol market has dramatically expanded in recent years. However, sugarcane's contribution toward fuel ethanol remains around 12%. This crop is in fact mainly being used for sugar production to meet the huge sugar demands of the country, and ethanol yielded from sugarcane molasses is majorly being diverted to beverages instead because of more competitiveness. The production of second-generation fuel ethanol from sugarcane bagasse is still under developmental stages, and its industrial production is limited by cost and challenges of efficiency of the pretreatment methods. However, for electricity cogeneration, sugarcane is already being extensively employed in Chinese sugar mills. With continuous increase in demand for renewable energy, along with the modernization of sugarcane production, advancements of breeding and processing technology, reduction of production cost, and favorable economic and governmental policy factors, we can expect that sugarcane will make a significant contribution to the biofuels production in southern China.

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Chapter 8
Biofuel Production from Sugarcane in Thailand

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and Sébastien Bonnet**

8.1 An Overview of the Thai Sugarcane Industry

Thailand is recognized as an agro-industrial-based country where several crops such as rice, cassava, and sugarcane are grown and exported as commodities. Sugarcane is a staple crop playing an important role in the Thai economy, not only for sugar production but also for bioenergy such as bioelectricity and biofuel production.

8.1.1 Sugarcane Production

Sugarcane can be grown well nationwide due to the tropical climate with average annual rainfall of about 1200–1600 mm. a year, except in the Southern region where the average rainfall is much higher, i.e., around 4500 mm a year, which is not suitable for sugarcane cultivation. With a total annual sugarcane production of about 94 million tons and the exportation of about 6.5 million tons of sugar in 2015/2016 (Office of Agricultural Economics Bangkok [OAE] 2016), Thailand has become the fifth largest producer and second largest exporter of sugar in the world. The country's average sugarcane yield is about 57 tons ha^{-1} (OAE 2017). In 2016, sugarcane plantations covered a total area of about 1.65 million ha. Figure 8.1 shows the expansion of sugarcane plantations in the country over the past decade, increasing on average by about 3% per year over the period 2008/2010 to 2016/2017

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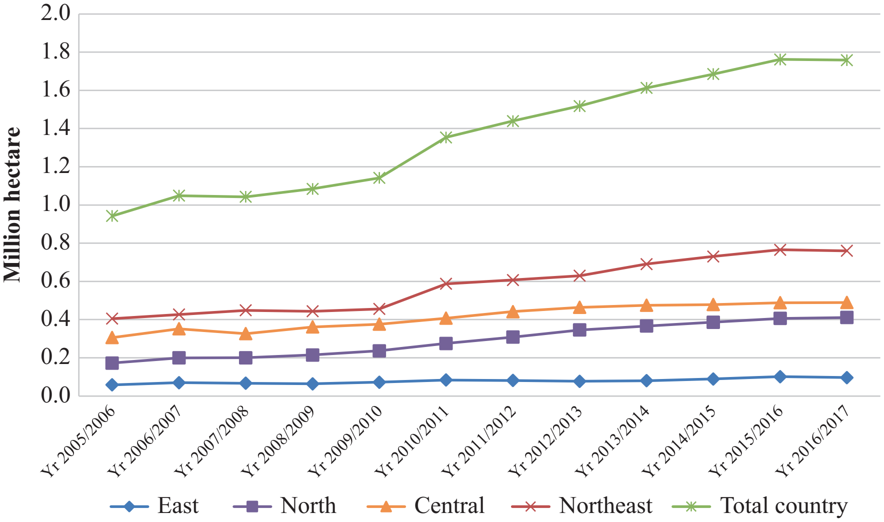

Fig. 8.1 Sugarcane plantation areas in Thailand by regions from year 2005–2016

(OAE 2017). Nevertheless, sugarcane cultivation in Thailand is mainly rainfed; the sugarcane production therefore could vary slightly year by year due to the climate situation such as drought and floods. For example, in the crop year 2016/2017, the harvested area decreased by 4% from the year 2015/2016 due to the drought impacts. This led to a decrease in sugarcane production from 94 million tons in 2015/2016 to 90 million tons in 2016/2017. The Northeastern region shared about 45% of the total sugarcane production, followed by the Central 29% and Northern 26% regions, respectively (OAE 2016).

8.1.2 Sugar Production

As per 2016, there are 52 sugar mills with a total annual sugarcane production capacity of about 94 million tons (OAE 2016). This corresponds to an annual sugar output of about 11.2 million tons. Since the annual domestic consumption of sugar was only 2.6 million tons, this surplus sugar production led Thailand to be the 2nd largest sugar exporter. The domestic consumption of sugar can be classified into direct consumption (52%) and indirect consumption by the industries including beverages (21%), food (12%), dairy products (10%), and others (5%). For export, the sugar products can be classified into raw sugar and refined sugar with an export of about 3.4 and 2.7 million tons, respectively (OAE 2016). The two major producers are Mitr Phol and Thai Roong Ruang, which contribute 21% and 15% of the total production capacity of sugar, respectively (Petchseechaung 2016). Worldwide, both groups are ranked the third and fourth largest exporter of sugar, respectively.

In 2016, the Thai sugarcane industry brought an income of more than 2578 million USD to the country from the export of sugar, as reported by the Office of the Cane and Sugar Board, Bangkok (OCSB 2017a). In addition, the sugarcane industry contributes a major role in the development of the Thai rural economy with over 364,000 households nationwide associated with sugarcane plantations, which are mostly represented by small-scale farmers (OAE 2016). At present, more than 75% of the total production of sugar is exported to major customers in the Asian region where Thailand has advantage due to cheaper transportation costs. This includes, notably, Indonesia (20% of total domestic sugar output), Myanmar (13%), China (13%), and Japan (9%). With regard to domestic consumption, direct household consumption contributes 55%, while the remaining portion is used in the manufacturing sector, including for the production of beverages, foods, and dairy products (OCSB 2017b).

8.1.3 Power Generation

One of the by-products of sugar milling, bagasse, has been used as fuel for heat and power generation for sugarcane production with excess electricity being sold to the national grid. Currently, the total installed capacity of electricity generation using alternative energy in Thailand is 9437 MW, comprising large hydropower plants (31%), biomass (30%), solar energy (26%), wind (5%), biogas (5%), small hydropower (2%), and municipal solid waste (1%) (Department of Alternative Energy Development and Efficiency [DEDE] 2016). For biomass power plants, the sugar industry plays an important role as power producer. The potential of power generation depends on the type of boilers and turbines and operating configurations (pressure and temperature) of the cogeneration systems. In general, sugar mills in Thailand operate boilers and back pressure steam turbines with a steam pressure of about 20 bar and temperature 350–360 °C. The plants produce energy for their own needs (sugar milling) with only some excess electricity being exported to the national grid (Jenjariyakosoln et al. 2014). However, due to the promotion of Small Power Producer (SPP) (10–90 MW) and Very Small Power Producer (VSPP) (<10 MW) schemes, recently, several sugar mill owners have established units of high-pressure boilers that produce steam at 103 bar and 515 °C in their new businesses which generate high amount of surplus electricity for exporting to the grid. However, this type of power plant will require biomass fuel in addition to bagasse during the off-season period of sugar milling. The 48 sugar mills in Thailand surveyed by Jenjariyakosoln et al. (2014) used 20 bar, 30 bar, 40 bar, 70 bar, and 103 bar steam pressure boilers. The major group of cogeneration technologies used in Thai sugar mills is the 20 bar configuration, found in 28 sugar mills; this actually represents a small range of boilers with pressures varying between 20 and 28 bars. Meanwhile, there were 6 sugar mills that used extraction condensing steam turbines ranging between 70 bar and 103 bar.

Several supporting schemes and incentives for SPP and VSPP have been adopted such as the feed-in premium tariff, exemption of investment tax scheme, soft loans for renewable energy, and fund provisions for renewable energy investments (Jenjariyakosoln et al. 2014). Table 8.1 shows the installed capacity of SPP and VSPP of the Thai sugarcane industry in 2015 (DEDE 2016)

8.2 Sugarcane Biofuel Development in Thailand

Sugarcane molasses, a by-product from sugar milling, has been promoted as feedstock for ethanol production. Its production has continuously been increasing since 2004 when it was first introduced on the market as a result of the Thai government policy to promote renewable energy (Silalertruksa and Gheewala 2010). In 2016, about 59% of the total production of ethanol came from molasses, followed by cassava (37%) and sugarcane juice (4%). The production of ethanol directly from sugarcane juice is not yet established in Thailand as a result of the restriction of the Cane and Sugar Act B.E.2527 (A.D.1984) which specifies that sugarcane juice is to be used only for sugar production.

8.2.1 The Government Policy on Biofuel Promotion

Since 2004, the Thai government has been promoting biofuels for transport in order to reduce oil imports and spur rural development. In 2008, Thailand's 15-Year Renewable Development Plan (REDP 2008–2022) was implemented, and ethanol derived from cane molasses, cassava, and sugarcane was strongly promoted by the government to partially substitute conventional gasoline. At the beginning, promotion strategies started from blending 10% ethanol in gasoline (so-called E10), the ethanol replacing the methyl tertiary butyl ether (MTBE). In 2008, as E10 was already well-established on the market, a 20% ethanol blend (E20) was introduced. Later on in the same year, E85 gasohol was launched. At that time, ethanol producers were also encouraged to support the market through Board of Investment (BOI)

Table 8.1 Installed capacity of SPP and VSPP of the Thai sugarcane industry

		Sugar mills	New power plants owned by sugar mills
	Type of contract	Installed capacity (MW)	Installed capacity (MW)
VSPP	Non-firm	737	355
SPP	Non-firm	131	476
SPP	Firm	–	193
Total		868	1024

Remark: Firm power purchasing agreement (Firm PPA) is a contract under which operators need to supply power as required by the Electricity Generating Authority of Thailand to ensure the state enterprise gets the exact energy supply specified in the contract privileges for fuel ethanol plants (Silalertruksa and Gheewala 2010). At present, all three gasohol blends are available nationwide. In 2012, the 10-Year Alternative Energy Development Policy (AEDP 2012–2021) was adopted to replace the REDP 2008. In that plan, the Thai government set a target where renewable energy should contribute 25% of the country's final energy consumption by 2021 (DEDE 2012). Energy from biomass, biogas, municipal solid wastes, as well as first-generation biofuels from indigenous feedstocks like molasses and cassava and advanced generation biofuels from agricultural residues have therefore been gaining much attention and been expanded.

As shown in Table 8.2, the production of ethanol has continuously been increasing from 1.2 ML per day in 2010 to 3.7 ML per day in 2016 (DEDE 2017). One of the reasons for the significant increase in the production of ethanol for transport in recent years is the embargo on the use of gasoline 91 (octane 91) by the government in January 2013. The growing demand for biofuels in the country so far is the result of a variety of policy instruments such as price subsidies, blending mandates, and tax exemption. In 2015, the renewable development plan was revisited and updated again into what is known as the Alternative Energy Development Plan: AEDP 2015 (2015–2036). In the new AEDP 2015, ambitious goals for ethanol production have been set with a production target of 11.3 ML per day to be achieved by 2036 (Energy Policy and Planning Office [EPPO] 2015).

8.2.2 *Current Situation of Ethanol Production and Use*

As of 2016, there are 21 existing ethanol plants in Thailand which consist of 14 molasses-based ethanol plants, 6 cassava-based ethanol plants, and 1 sugarcane juice-based ethanol plant (Table 8.3). The total ethanol production capacity amounts to 4.19 million liters (ML) per day with 64% from molasses, 31% from cassava, and 5% from sugarcane juice (Bank of Thailand 2017).

As mentioned earlier and also illustrated in Fig. 8.2, there has been a continuous increase in the production and consumption of ethanol in Thailand over the period 2007–2016. This is consistent with the increasing trend in the consumption of gasohol in the form of E10, E20, and E85 as illustrated in Fig. 8.3. Although ethanol is promoted mainly for domestic consumption, there is a great potential for export. Statistics reveal that since 2007 up to the end of 2009, 91 million liters of surplus

Table 8.2 Biofuel production in Thailand (ML per day)

	2010	2011	2012	2013	2014	2015	2016
Ethanol	1.2	1.2	1.4	2.6	3.2	3.5	3.7
Biodiesel	1.7	2.1	2.7	2.9	2.9	3.3	3.4
Total	2.9	3.3	4.1	5.5	6.1	6.8	7.1

DEDE (2017)

Table 8.3 Ethanol factories in Thailand (as of 2016)

	No. of ethanol plants by feedstocks used				Production capacity			
Region	Molasses	Cane juice	Cassava	Total	Molasses	Cane juice	Cassava	Total
North	1	1	–	2	0.23	0.23	–	0.46
Northeast	4	–	2	6	0.98	–	0.53	1.51
Central	8	–	1	9	1.32	–	0.20	1.52
East	1	–	3	4	0.15	–	0.55	0.70
Total	**14**	**1**	**6**	**21**	**2.68**	**0.23**	**1.28**	**4.19**

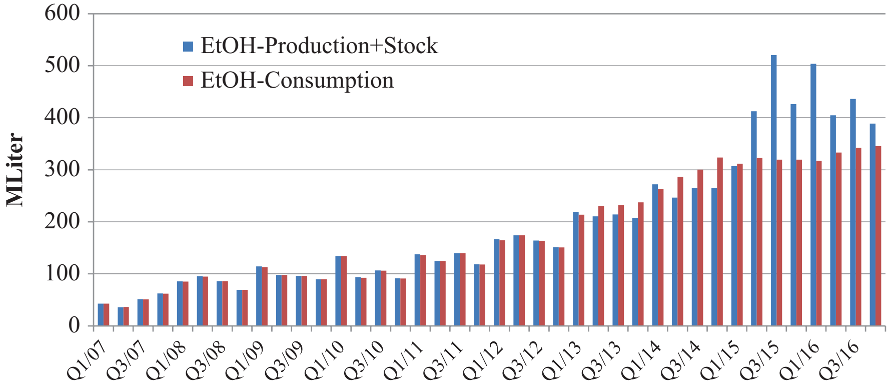

Fig. 8.2 Ethanol production and consumption in Thailand during 2007–2016 (by quarter). (Data sources: DEDE (2017) and BOT (2017))

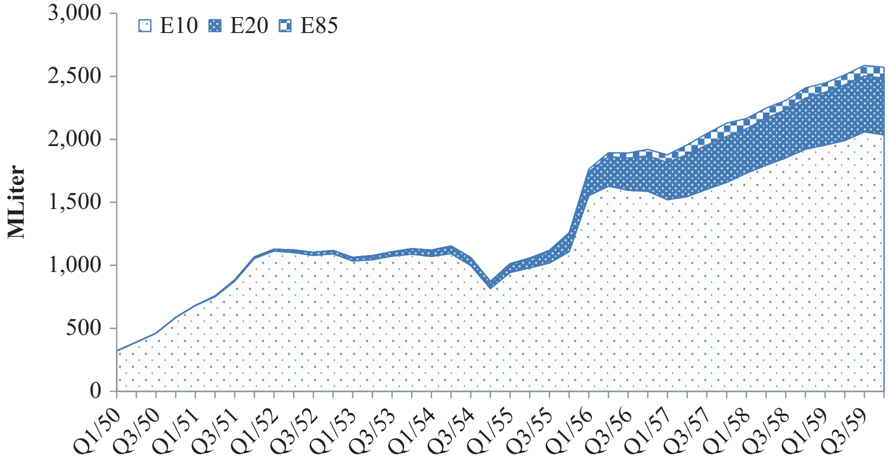

Fig. 8.3 Gasohol consumption in Thailand during 2006–2016 (by quarter) (Department of Energy Business 2017)

ethanol was exported to countries such as Singapore, EU, Australia, and the Philippines (Silalertruksa and Gheewala 2010).

The biofuel industry has been growing steadily, boosted by supportive government measures. One of the key policy measures driving the biofuel growth in the country is the mandate requiring the replacement of a certain volume of petroleum-based fuel by biofuel. In addition, for the consumer side, tax exemption has been used to spur the biofuel demand. The key reason behind the government's support for biofuels is to curb reliance on fossil fuel imports and strengthen Thailand' energy security. In addition, biofuel production from agricultural raw materials provides an alternative outlet for farmers and adds value to agricultural products.

8.3 Challenges on Sustainability of Sugarcane Ethanol Production

Although sugar and sugarcane bioenergy have now developed into a relatively mature industry in Thailand, there still are several issues of concern regarding certain aspects of environmental sustainability, such as open burning of cane trash and related emissions, life cycle greenhouse gas emissions of sugarcane ethanol production, and eutrophication impacts associated with vinasse production from molasses ethanol plants (Gheewala et al. 2011; Silalertruksa and Gheewala 2009; Silalertruksa et al. 2017). In addition, to fulfill the ambitious goals of the Thai government's ethanol policy development plan, there are a number of risks and undesirable development effects associated with large-scale production and use of sugarcane for bioenergy as well as unregulated expansion of bioenergy (Pereira and Ortega 2010). For example, the rapid increase in the demand for sugarcane ethanol has led to increasing concerns over the potential competition between food and biofuels for arable land and freshwater resources as well as greenhouse gas (GHG) emissions from the various life cycle stages leading to biofuel production (Global Bioenergy Partnership [GBEP] 2011). The use of inputs, including agrochemicals, fertilizers, fuel and materials, as well as the emissions and wastes generated from sugarcane production systems, contributes to environmental impacts such as climate change, eutrophication, resource depletion, etc. (Silalertruksa and Gheewala 2009; Pongpat et al. 2017). The future expansion of sugarcane plantations for ethanol production may also potentially lead to water scarcity impact in some Northeastern areas of Thailand (Gheewala et al. 2013). Moreover, monocultures may contribute to soil degradation and natural ecosystem destruction.

Apart from the broad sustainability concerns associated with the expansion of sugarcane bioenergy, the sugar industry needs to improve its environmental and economic performance. Over the past few years, many initiatives have been developed to address the environmental and socioeconomic impacts associated with the production of biofuels or specific biofuel feedstocks. These initiatives include regulatory frameworks and voluntary standards/certification schemes. The key sustainability standards that are relevant to sugarcane ethanol and gaining attention among academia, industries, and policy makers include the following: EU-RED (2016) (EU Renewable Energy Directive), US-RFS (US Renewable Fuel Standards), Bonsucro (Bonsucro 2015), GBEP (Global Bioenergy Partnership) (GBEP 2011), and SAFA (Sustainability Assessment of Food and Agriculture) (FAO 2014) (Table 8.4). Currently, there is relatively little scientific information available regarding the sustainability of the sugarcane supply chain, taking into consideration all of the environmental, economic, and societal aspects. Only some particular aspects, especially GHG emissions, have been investigated and discussed through the view of life cycle assessment (LCA) (International Organization for Standardization 2006) and carbon footprint of products.

8.3.1 Life Cycle Greenhouse Gas Emissions

Based on the principle that plants grown as feedstocks for biofuel production absorb carbon dioxide (CO_2) from the atmosphere through the photosynthesis process, it is considered that the combustion of ethanol simply releases the CO_2 previously absorbed by the plant. This carbon neutral concept is one of the environmental advantages of ethanol as compared to fossil fuels. However, one of the controversial issues related to biofuel production systems is whether they can help reduce dependency on fossil energy and reduce GHG emissions over their entire life cycle. Life cycle assessment (LCA) has therefore been widely used to identify and evaluate the potential environmental implications of biofuels in order to improve their environmental performance. The studies have so far largely been limited to greenhouse gas (GHG) emissions of molasses ethanol (Silalertruksa and Gheewala 2011). The GHG emissions of molasses ethanol have been found to vary over a wide range from 28 to 119 g CO_2 eq MJ^{-1} depending on the production systems considered. The emissions depend on a large number of factors, including, for instance, the types of fuel used for steam generation in the ethanol plant, the system of biogas recovery, etc. (Silalertruksa and Gheewala 2011). The highest GHG emission value reported above is specific to a molasses ethanol plant where imported coal is used as fuel for its boiler. The lowest value is derived from an integrated sugar mill and ethanol plant where steam and power are produced from bagasse. In general, the results indicate that molasses ethanol production is a good substitute for gasoline in terms of GHG emissions. Nevertheless, the inclusion of land-use change (LUC), both direct and indirect, in the assessment of life cycle GHG emissions of biofuels is still a controversial issue. It can contribute significantly to increase the overall GHG emissions of biofuels (Kim et al. 2009; Silalertruksa and Gheewala 2011; Prapaspongsa and Gheewala 2016). However, a wide range of GHG emissions from LUC can be observed depending on the modelling choices made and systems affected (Prapaspongsa and Gheewala 2016).

Table 8.4 Sustainability standards and aspects of sugarcane biofuel production

		Environmental aspects								Economic aspects			Social aspects			
		Resource consumption				Emission										
Standards	Product categories	Land use	Water quantity	Fossil fuel	Biodiversity	Air quality	GHGs and other impacts	Water quality	Soil quality	Productivity	Profitability	Trade	Human rights	Social well-being	Social acceptability	Food security
GBEP	Bioenergy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
SAFA	Food and agricultural systems	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
EU-RED	Bioenergy	✓	✓	✓	✓	✗	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗
Bonsucro	Sugarcane and related products	✓	✓	✓	✓	✓	✓	✗	✓	✓	✗	✗	✓	✓	✓	✗

8.3.2 Land and Water Competition

In recent years, concerns over the impacts of the biofuel boom on food security have been the subject of much debate worldwide. Arable land is very limited and land demand for growing crops to serve both food and energy production has continuously been increasing. Could this result in an increase in food prices? Of course, biofuels should not be considered as being mainly responsible for the rise in food prices. There is a plethora of factors which may contribute to this increase. These include higher production costs due to rising oil prices, production shortfalls due to climatic events, changes in consumption patterns due to changes in income, weak currency exchange rates, stock level, and market volatility.

In Thailand, agricultural land covers 23.9 million ha and represents around 46% of the nation's surface (OAE 2016). Rice is the main cash crop grown nationwide, covering an area representing about 47% of the agricultural land (or 11.2 million ha), followed by perennial crops (including orchards) and cropland which share about 23 and 21% of the agricultural land, respectively. Para rubber and oil palm are the major perennial crops grown in the Southern part of the country covering 3.7 million ha and 0.7 million ha, respectively. For cropland, aside from rice, sugarcane, cassava, and maize are among the main cash crops grown in Thailand covering an area of 1.4, 1.3, and 1.2 million ha, respectively (OAE 2016). Also, the promotion of sugarcane plantation, including its expansion on areas occupied by low-productivity upland paddy fields, has been introduced as an option to increase farmers' income, reduce water consumption, and fulfill the excess capacity of existing sugar mills. The current target is set at about 0.37 million ha in areas occupied by low-productivity upland paddies in the Northeastern and Central regions of the country. This regional expansion of sugarcane may lead to various impacts on land, water, and GHG emissions depending on factors such as soil conditions, rainfall, water stress situation, agricultural practices, and productivity.

Apart from the land-use issue, freshwater scarcity and competition are other challenges of interest as agriculture is recognized as the world's largest water-consuming sector. It accounts for about 70% of global freshwater withdrawal (WWAP 2012). Thus, for instance, it has been estimated that, to achieve the Thai government policy production target of 9 million liters per day ethanol by 2021, additional irrigation water of 1625 million m^3 $year^{-1}$ would be required. In the *Mun* and *Chi* watersheds of Thailand, water competition issues have been identified among domestic, industry, and agricultural sectors for food and biofuel production if the water resources there are not properly managed (Gheewala et al. 2013). Measures to reduce the water scarcity footprint are, therefore, to be addressed by policy makers to not compromise the sustainability of biofuel production. In addition, the policy related to the conversion of low-productivity upland paddy fields to sugarcane plantations has been evaluated to determine its implications on the monthly water stress index of relevant watersheds and the water scarcity footprint potentials of rice and sugarcane production (Gheewala et al. 2017). The results have shown that proper policy measures can help in reducing the amount of water required for agriculture in the months of June, July, August, and September by about 60–220 Mm^3, which in turn results in the decrease in monthly water stress index values (Gheewala et al. 2017). Nevertheless, appropriate measures of water resource management for agriculture still need to be designed to avoid water competition issues as well as to protect the ecosystem.

8.3.3 Waste and By-Product Management

Although sugar and sugarcane bioenergy have now been developed into a relatively mature industry in Thailand, there are several issues of concern regarding environmental sustainability. For example, cane-trash burning during harvesting is recognized as a major issue of air pollution and soil degradation, which needs to be appropriately addressed (Silalertruksa and Gheewala 2009; Souza et al. 2012).

The potential environmental impact related to the production of vinasse from molasses ethanol plants is also another important challenge for the sugarcane ethanol industry (Gheewala et al. 2011). Moreover, there is a variety of by-products generated from the sugarcane value chains, such as cane trash (if green-cane harvesting were adopted) from sugarcane cultivation, filter cake and wastewater from sugarcane milling, vinasse from ethanol production, and ash from steam and power generation. All these biomass streams need to be managed properly to secure their benefits (Silalertruksa et al. 2017). The promotion of both appropriate farming practices and the integrated utilization and management of the by-products and wastes generated over the entire life cycle of sugarcane production systems is essential to the future competitiveness of the sugarcane industry. The integrated use of sugarcane biomass materials generated from the mills can be highly competitive with other crops as preferred feedstock for a biomass-based industry (Renouf et al. 2008).

8.3.4 Socioeconomic Risks

Large-scale industrialized investment impacts and labor working conditions are social and economic risks relevant to biofuels. These are aspects of concern covered in international standards for sustainable agriculture and bioenergy production, including the GBEP, Bonsucro, as well as SAFA. In the world of rural agriculture, family businesses or cooperatives may be displaced by large-scale industrialized farms. The strength or weakness of this transformation is difficult to assess as large-scale industries may be able to achieve much larger crop yields and production volumes than small farms. However, this also leads to dispossession of land from local farmers which is a very sensitive issue as well as employment problems. The standard of labor conditions needs to be taken into account to ensure that workers can get acceptable levels of wages and working hours as well as to prevent child labor (FAO 2014; GBEP 2011; Smeets et al. 2008). In Thailand, nowadays, the sugarcane industry is trying to shift from traditional sugarcane production systems to more mechanized ones (from cultivation to harvesting). This is to solve the issue of labor shortage occurring during the harvesting season as well as to increase benefits from sugarcane biomass utilization. The Thai sugarcane industry is currently very strict on the standards of labor conditions covering labor in the farms and in the processing industries. Several activities have been initiated involving participation of both sugar millers and local communities to improve the local economy, cultural conservation, education as well as other activities pertaining to the corporate social responsibility policy of each mill. The survey on social aspects of concern for different stakeholders involved in the sugarcane supply chain has revealed that workers attached more significance to issues relating to fair wages, followed by occupational health and safety (Gheewala et al. 2016). The sugar industry is thought to help improve local employment and contribute to economic development, delocalization, and migration by local community groups. However, there still are some concerns on health issues related to air pollution from cane open burning and transport. Water and land rights are also gaining increasing attention from the value-chain actors.

8.3.5 Competitive Crops for Ethanol Production

Several competing crops to sugarcane for biofuel production have been considered by the Thai government so far such as cassava, sweet sorghum, and maize, as well as second-generation ethanol from agricultural residues. At present, only cassava is considered as alternative feedstock to sugarcane in view of its availability and technical and economic viability for commercialization. Thailand is recognized as one of the world's top exporters of cassava products. As mentioned earlier, cassava plantations occupy an area of about 1.3–1.4 million ha nationwide as for sugarcane (OAE 2016). In general, cassava farmers can easily shift their cultivations between cassava and sugarcane depending on the price of their products. Cassava is used for food and feed production in the form of starch, chips, and pellets as well as for ethanol production. With regard to ethanol, there is an increasing number of cassava-based ethanol plants in the country which include new individual cassava ethanol plants and multi-feedstock ethanol plants (molasses and cassava). There are currently 47 ethanol plants officially registered with the government to produce ethanol for transport with a total capacity of around 12.3 million liters per day. This consists of 14 factories using molasses with a total production capacity of 2.48 million liters per day, 25 factories using cassava with a total production capacity of 8.59 million liters per day, and one factory using sugarcane juice with a total production capacity of 0.2 million liters per day (Sriroth et al. 2010). A multi-feedstock process using both molasses and cassava is however preferred in some factories

(7 factories with a total production capacity of 1.02 million liters per day) in order to avoid shortages of feedstock which eventually ends up with high-priced feedstock (Sriroth et al. 2010).

8.4 Sugarcane Biorefinery for Sustainability of Sugarcane and Sugarcane Ethanol Industry

8.4.1 Existing Sugarcane Biorefinery in Thailand

Nowadays, the Thai sugarcane industry is trying to shift to more mechanization in the farming stage as well as to increase benefits from sugarcane biomass utilization. The production systems that integrate biomass conversion processes to produce fuels, heat, electricity, and value-added products from biomass, or so-called biorefineries, are therefore gaining increasing attention in the sugarcane industry, e.g., the sugar-ethanol-electricity mills and the integrated first- and second-generation ethanol production (Dias et al. 2013; Silalertruksa et al. 2017). As per the biorefinery concept, if the waste is properly treated, the industries will be able to benefit from both the reduction of end of pipe treatment costs and the creation of value from waste utilization. The promotion of adequate farming practices as well as the integrated utilization and management of by-products and wastes generated over the entire life cycle of sugarcane production systems are essential to the future competitiveness of the sugarcane industry.

An example of a sugarcane biorefinery (sugar-power-ethanol production) in Thailand is shown in Fig. 8.4. The system integrates sugar production from sugarcane juice and biomass conversion processes to produce molasses ethanol, steam, and electricity. In this system, mechanized farming is adopted, and 50% of cane trash is recovered for power generation. In addition, vinasse is recovered and returned to the sugarcane field as organic fertilizer and soil conditioner. This type of sugarcane biorefinery can contribute to significantly reduce several environmental impacts as compared to a traditional (sugar-power-ethanol) system in which cane trash is subject to burning before harvesting (conventional farming practices) and vinasse and wastewater from ethanol conversion processes are kept in open ponds. The biorefinery system illustrated in Fig. 8.4 contributes to reduce the environmental impact potentials of molasses ethanol as compared to a conventional system by 40% for climate change, 60% for acidification, 90% for photo-oxidant formation, 63% for particulate matter formation, and 20% for fossil depletion. These results are summarized in Table 8.5 (Silalertruksa et al. 2017). The reduction in these environmental impacts comes from the avoidance of cane-trash burning and the additional credits obtained from cane-trash recovery for power generation where the surplus electricity is sold to the Thai grid, thus substituting for electricity generated from fossil fuels, i.e., natural gas and coal. The use of vinasse as organic fertilizer provides credits from the substitution of chemical fertilizers.

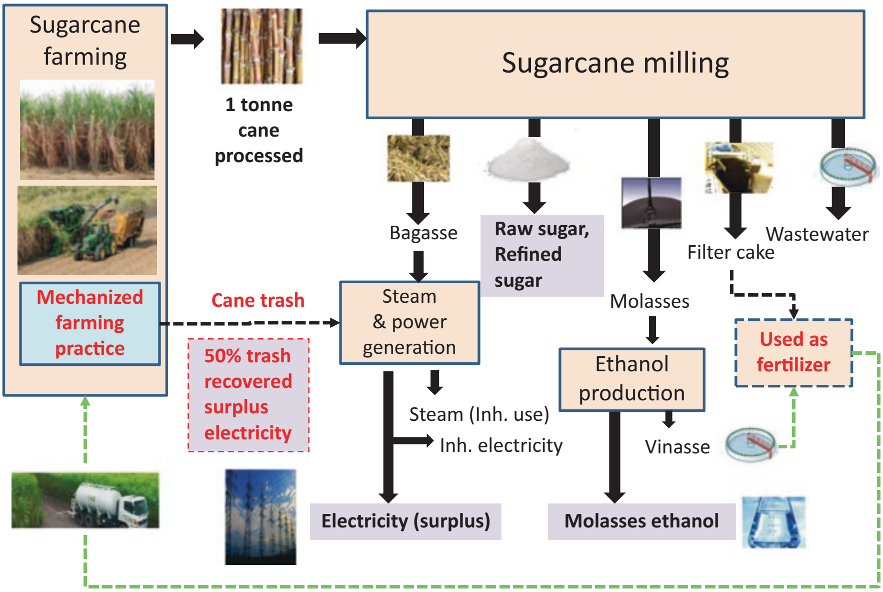

Fig. 8.4 Sugarcane biorefinery system in Thailand

Table 8.5 Environmental impact potentials of 1000 liters molasses ethanol

Impact category	Unit	Traditional system	Improved system (as in Fig. 8.4)
Climate change	kg CO_2 eq	509	309
Terrestrial acidification	kg SO_2 eq	3.3	1.3
Freshwater eutrophication	kg P eq	0.07	0.07
Human toxicity	kg 1,4-DB eq	99	94
Photochemical oxidant formation	kg NMVOC eq	8.0	0.9
Particulate matter formation	kg PM10 eq	1.2	0.5
Terrestrial ecotoxicity	kg 1,4-DB eq	0.05	0.05
Freshwater ecotoxicity	kg 1,4-DB eq	2.5	2.3
Fossil depletion	kg oil eq	70	56

Silalertruksa et al. (2017)

8.4.2 Prospective Sugarcane Biorefinery

At present (year 2017), the Thai government is taking serious steps to move the country toward Thailand 4.0 which is a new economic model focusing on a value-based economy in order to pull Thailand out of the middle-income trap and develop it as a high-income country. The bio-economy industry is one of the government's target industries and is part of the five future industries in the New S-Curve under the Thailand 4.0 policy. Existing cash crops like sugarcane and cassava are expected

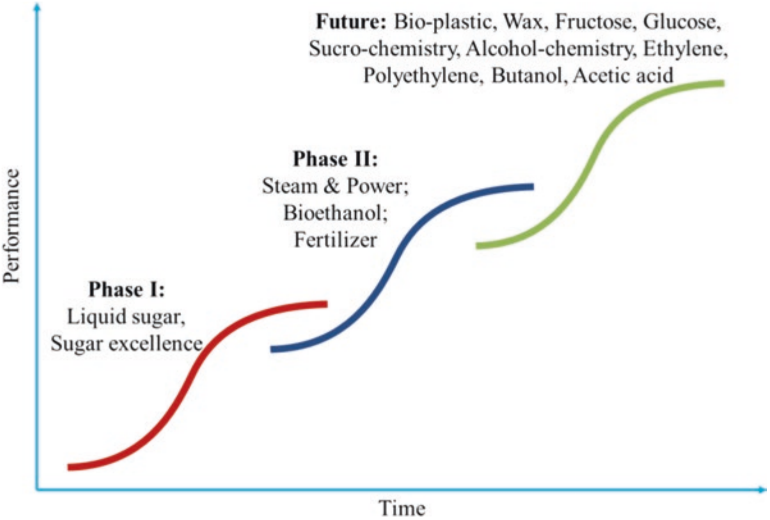

Fig. 8.5 Development of sugarcane products under sugarcane biorefinery concept

to be used to develop high-value products in an effort to build a bio-economy. Figure 8.5 shows the prospective sugarcane-based products which the sugarcane industry as well as the government are looking forward to develop in the future, not only with regard to high-quality biofuels but also high value-added products, including biochemicals and bioplastics.

8.5 Conclusion

Sugarcane ethanol plays an important role for transport as a substitute to fossil fuel in Thailand. With a total production capacity of 4.19 million liters per day, sugarcane accounts for 69% of the total ethanol production (molasses ethanol represents 64%, whereas sugarcane juice accounts for 5% of the total production), the remaining 31% being contributed by cassava. The demand for ethanol is expected to continue to increase in future based on the AEDP policy production target set by the Thai government, which stands at 11.3 million liters per day by 2036. In line with rising global concerns over climate change and its mitigation, efforts in promoting renewable energy via the AEDP are guaranteed to be sustained as providing key policy measures to drive the country toward achieving its Intended Nationally Determined Contributions (INDC), i.e., 20% reduction in GHG emissions by 2030 and a maximum target of 25% as compared to 2005 level (Business as Usual scenario). Under the AEDP, the sugarcane industry is expected to play an important role not only for sugarcane ethanol production but also for power generation from bagasse under the Independent Power Producers (IPP) and Small Power Producers

(SPP) schemes. However, there are risks and undesirable developments that may result from large-scale expansion of sugarcane plantations as well as sugarcane ethanol and bioenergy production unless adequate regulatory measures are implemented. Key sustainability concerns include life cycle GHG emissions, land and water use competitions for food and fuels, water scarcity and water deprivation potential, as well as impacts on human health and the ecosystem due to wastewater and air pollutant emissions. However, there is increasing awareness that sugarcane and its co-products, such as cane trash, bagasse, molasses, and filter cake, can be used as part of a biorefinery system to produce a wide range of products, including, ethanol, electricity as well as chemicals, in particular a variety of polymers. LCA studies have shown that sugarcane-based biorefinery systems involving a mechanized farming stage and maximized utilization of cane trash and vinasse for power and fertilizer can bring a number of enhanced environmental benefits, notably with regard to climate change, acidification, photo-oxidant formation, particulate matter formation, and fossil fuel depletion. Finally, according to the country's strategy on Thailand 4.0, a new economic model focusing on a value-based economy, sugarcane is one of the main cash crops expected to contribute developing high-value products in an effort to build a bio-economy. Hence, the sugarcane industry in the future is anticipated to play a major role not only for the production of ethanol and sugar but also for the production of biochemicals and bioplastics.

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Chapter 9
Sugarcane Biofuels and Bioenergy Production in Pakistan: Current Scenario, Potential, and Future Avenues

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9.1 Introduction

Sugarcane, the largest crop commodity with respect to total production, is grown in more than 70 countries all over the world to meet the global sugar needs (FAOSTAT 2017). However, it is also one of the most suitable sources of bioenergy as it exhibits the highest number of the major characteristics for an energy crop. Sugarcane is among worlds' best photosynthesizers and sucrose producers. Moreover, it records the greatest output to input ratio for biofuel engenderment, making it one of the most efficient crops for the purpose (Khan 2018). Further, the automated harvest technology for sugarcane, no requisites of prime agricultural lands in certain countries, and the already established sugar industry make the crop one of the best fits for the product.

Sugarcane also addresses one of the major concerns against biofuel crops, i.e., food security, as it yields huge biomass supplying lignocellulosic materials—source of second-generation biofuels—which does not affect the food production (Khan et al. 2017b; Matsuoka et al. 2015). Presently, the ethanol production from sugarcane is mainly done from cane juice and molasses. Biomass and field leftovers can also be employed for obtaining cellulosic biofuels; however, the conversion of raw materials of the commodity into cellulosic biofuels is extremely intricate (Pereira et al. 2015). Once the second-generation approaches have been perfected, sugarcane can be excellently utilized for producing this class of biofuels, along with the traditional production of cane sugar and ethanol.

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Sugarcane bagasse can also find applications in electricity cogeneration, another form of bioenergy. Such energy would not only satisfy the requirements of the sugar mills, but surplus energy can be supplied to the national grids (Leal 2007). Even more, sugarcane sector can also provide biogas for domestic uses (Rabelo et al. 2011). It indicates that sugarcane plays vital role in providing energy to the major cane cultivating countries such as Brazil, India, China, Thailand, Pakistan, and many more.

Pakistan, being the fifth largest cane producer, can extensively employ sugarcane for meeting its fuel and energy requirements. The country spends huge foreign exchange for meeting oil needs of the country. Moreover, Pakistan is facing huge electricity shortfalls since many years. Thus, sugarcane can play important role in diversifying Pakistan's energy matrix, reducing oil imports, and adding bioelectricity to the national grid.

9.2 Sugarcane Crop Situation in Pakistan

Sugarcane is one of the most important cash crops of Pakistan. It is the largest crop of the country with respect to total production (Fig. 9.1) (FAOSTAT 2017). Sugarcane was farmed on area of 1.22 million ha (Mha) in the year 2017, while its total production was 73.40 million tons (MT). The sugarcane production has constantly increased in the country over time (Fig. 9.2). Pakistan ranks at fifth position in overall sugarcane cultivation in the world, following only Brazil, India, China, and Thailand (FAOSTAT 2017, Pakistan Bureau of Statistics [PBS] 2017).

According to Pakistan Economic Survey, the yield of sugarcane crop has increased from 55.98 t ha^{-1} in 2010, to 61.97 t ha^{-1} by 2017, whereas area as well as total production has also shown growth, generally, over the said period (Ministry of Finance [MoF] 2018). Sugarcane is being cultivated in all four provinces of the

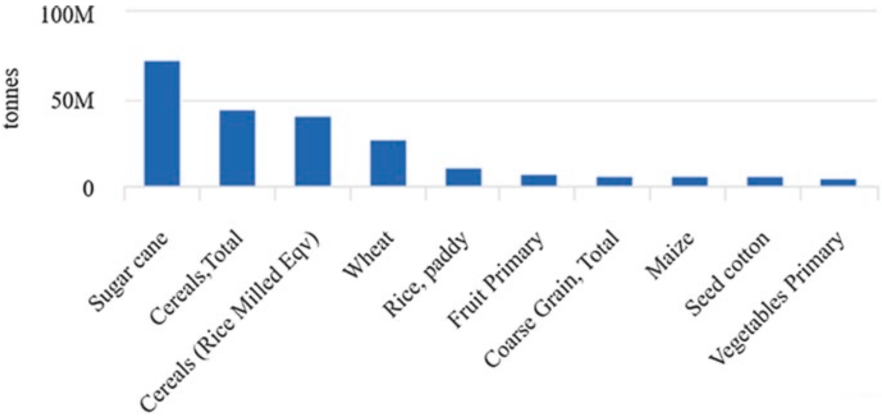

Fig. 9.1 Most produced commodities in Pakistan in 2017. (Source: FAOSTAT 2017)

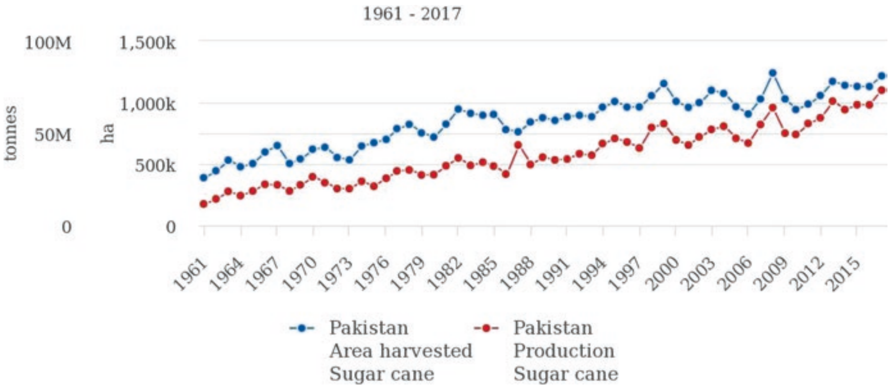

Fig. 9.2 Production and area of sugarcane cultivation in Pakistan from 1961 till 2017. (Source: FAOSTAT 2017)

country. Punjab, Sindh, and Khyber Pakhtunkhwa are growing the crop since independence, whereas its cultivation in Balochistan started in 1969. Punjab is the largest cane-producing province with total production of 49.61 MT, followed by Sindh, Khyber Pakhtunkhwa, and Balochistan. The Punjab province also leads in average sugarcane yield per hectare. Its yield is 63.78 t ha^{-1}, whereas Sindh, the second largest producer, harvests 63.05 t ha^{-1}. Khyber Pakhtunkhwa and Balochistan harvest 47.46 t and 45.14 t of sugarcane per hectare, respectively. The share of Punjab in sugarcane cultivation with respect to area under cultivation is 62%, while the other two major provinces, Sindh and Khyber Pakhtunkhwa, contribute for approximately 28% and 10% area, respectively (Punjab Agriculture Marketing Information Service 2017).

In recent years, the sugarcane production and area under cultivation have increased significantly. Improvements have also been observed in yield of the crop. However, the average sugar recovery has reduced from 10% to 9.87% over the last five cropping seasons. In the same period, however, total sugar production surged from 5.036 MT to 7.005 MT (Fig. 9.3) (Ministry of Finance 2018; Pakistan Sugar Mills Association [PSMA] 2018).

Sugarcane fulfils 99% sugar requirements of Pakistan, as sugar beet's cultivation is only marginal. Sugar industry is the second largest industry of Pakistan following only cotton sector. Pakistan is the greatest per capita sugar consumer of South Asia, surpassing the other three main sugarcane-growing countries in the region, i.e., India, China, and Thailand (Azam and Khan 2010). Sugarcane sector is also supporting production of various other products including alcohol, paper, and press mud. Moreover, raw material for confectioneries and chip board is also provided by the sugar mills. Additionally, its molasses is being exported for earning foreign exchange (Almazan et al. 1999). Contribution of the sugarcane sector toward total agricultural value addition is 3.1%, while its share in GDP of the country is 0.6% (MoF 2015).

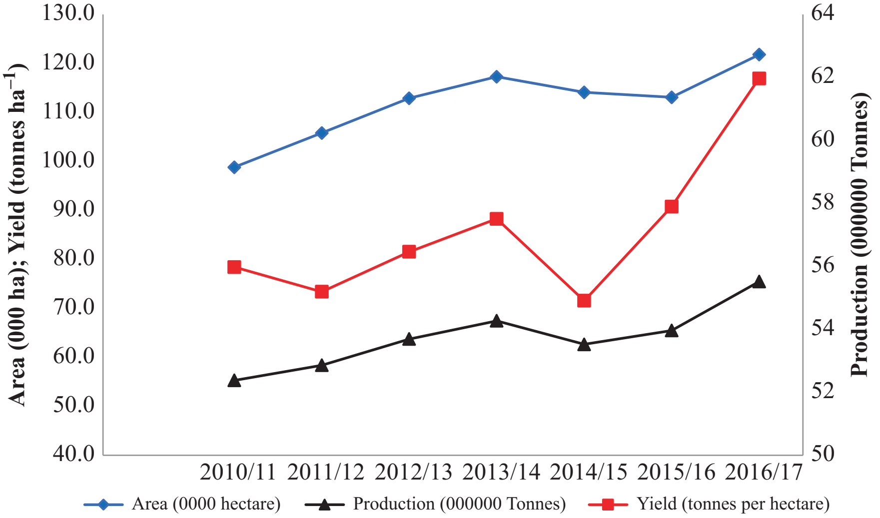

Fig. 9.3 Variations in total sugarcane production, area under cultivation, and per hectare yields of sugarcane in Pakistan since 2010 (Ministry of Finance 2018)

9.3 Sugar Industry of the Country

Sugar industry is a well-established industry in Pakistan. A total of 90 sugar mills are currently established in the country, out of which 45 are installed in Punjab, 38 in Sindh, and 07 in Khyber Pakhtunkhwa (PSMA 2017). Sugar mills in Pakistan, in season 2016–2017, crushed a total of 70.989 MT of sugarcane, manufacturing 7.005 MT of sugar (Table 9.1). The industry is currently producing surplus sugar and has potential to export the same. However, government policies discourage export of sugar as the country has suffered some severe sugar crisis in the past.

Industrial capacity of sugar mills is currently more than 70 million tons. Sugar industry of the country provides employment to 47,000 persons directly, and about a million overall. Mill-wise cane crushing, sugar production, recovery, and molasses engenderment data are presented in Table 9.2.

9.4 Energy Scenario of Pakistan

Pakistan does not have ample resources of energy to meet its needs (Table 9.3). Being a developing economy of more than 197 million people, the country has huge demands for petroleum as well as electricity. Petroleum requirements are fulfilled by imports from other nations, and thus, scarcity of oil resources creates one of the biggest burdens on country's import bills. Major traditional fuels used by automotive sector of Pakistan include petrol, diesel, liquefied petroleum gas (LPG), and compressed natural gas (CNG).

Table 9.1 Sugarcane crushing and sugar production in Pakistan (2010–2017)

Year	Mills	Cane crushed (tons)	Sugar produced (tons)
2010–2011	84	44,526,719	4,172,729
2011–2012	86	48,248,535	4,670,380
2012–2013	86	50,089,483	5,030,129
2013–2014	88	56,460,524	5,587,568
2014–2015	89	50,795,218	5,139,566
2015–2016	89	50,042,249	5,082,110
2016–2017	90	70,989,948	7,005,480

Source: PSMA (2017)

Table 9.2 Mill-wise sugar production in Pakistan during 2016–2017 season

Mill	Cane crushed (t)	Sugar production (t)	Recovery %	Molasses production (t)
		Punjab province		
Abdullah (Depalpur) Sugar Mills	276,714	25,250	9.12	12,452
Abdullah (Shahpur) Sugar Mills	Not operated			
Adam Sugar Mills	710,053	65,097	9.17	33,091
Ashraf Sugar Mills	1,529,531	151,585	9.91	78,628
Al-Moiz Sugar Mills – II	851,587	85,579	10.05	38,321
Baba Farid Sugar Mills	370,901	33,050	8.91	1669
Brothers Sugar Mills	Not operated			
Chanar Sugar Mills	630,374	58,035	9.21	31,800
Chaudhry Sugar Mills	522,958	52,070	9.96	23,533
SW Sugar Mills (Chishtian)	Not operated			
Colony Sugar Mills (Phalia)	Not operated			
Colony Sugar Mills (Punjab)	Not operated			
Etihad Sugar Mills	1,700,326	177,316	10.43	48,195
Fatima Sugar Mills	1,607,499	162,925	10.14	46,431
Darya Khan Sugar Mills (Fecto)	867,154	79,240	9.14	39,022
Hamza Sugar Mills	3,916,618	399,999	10.21	176,248
Haq Bahu Sugar Mills	322,568	29,676	9.2	14,516
Haseeb Waqas Sugar Mills	169,632	14,030	8.27	7,633
Huda (Fauji) Sugar Mills	495,605	47,350	9.55	22,302
Hunza Sugar Mills – I	1,068,352	96,295	9.01	48,076
Hunza Sugar Mills – II	852,231	79,914	9.38	38,350
Husein Sugar Mills	660,136	65,043	9.85	29,706
Indus Sugar Mills	1,449,023	146,699	10.12	55,250
Ittefaq Sugar Mills	426,707	41,830	9.80	19,202
Jauharabad Sugar Mills	546,857	53,972	9.87	15,990

(continued)

Table 9.2 (continued)

Mill	Cane crushed (t)	Sugar production (t)	Recovery %	Molasses production (t)
JDW Sugar Mills (United) – I	3,528,599	357,733	10.14	149,681
JDW Sugar Mills (United) – II	2,373,561	247,926	10.45	101,620
Two Star Sugar Mills	1,751,261	164,650	9.40	78,807
Kashmir Sugar Mills	664,661	61,931	9.32	29,710
Layyah Sugar Mills	1,831,557	176,520	9.64	82,420
Macca Sugar Mills	52,937	4450	8.41	2382
Madina Sugar Mills	1,205,955	115,416	9.57	54,268
Noon Sugar Mills	1,115,492	113,308	10.16	16,845
Popular Sugar Mills	668,764	66,159	9.89	30,094
Pattoki Sugar Mills	727,161	63,405	8.72	32,772
Ramzan Sugar Mills	982,208	93,709	9.54	44,199
Rasool Nawaz Sugar Mills	389,461	37,410	9.61	17,526
RYK Sugar Mills	1,728,228	168,116	9.73	77,770
Safina Sugar Mills	1,038,142	102,788	9.90	46,716
Shahtaj Sugar Mills	1,148,874	115,754	10.08	48,947
Shakarganj Sugar Mills – I	838,456	77,527	9.25	37,731
Shakarganj Sugar Mills –II	705,393	66,917	9.49	31,743
Sheikhoo Sugar Mills	2,340,612	222,539	9.51	105,328
Tandlianwala Sugar Mills – I	702,070	62,542	8.91	31,593
Tandlianwala Sugar Mills – II	1,375,104	130,474	9.49	61,883
Khyber Pakhtunkhwa				
AL-Moiz Sugar Mills	985,695	99,892	10.13	44,356
Chashma Sugar Mills – unit I	1,368,854	125,119	9.14	61,598
Chashma Sugar Mills – unit II	855,640	78,567	9.18	38,500
Khazana Sugar Mills	259,847	26,285	10.12	11,693
Premier Sugar Mills	268,864	25,047	9.94	12,030
Tandlianwala (Zamand) Sugar Mills	1,109,909	102,416	9.23	49,948
Bannu Sugar Mills	Not operated			
Sindh				
Al-Abbas Sugar Mills	659,154	70,848	10.69	30,277
Abdullah Shah Ghazi Sugar Mills	16,941	1200	7.08	762
Al-Noor Sugar Mills	1,315,682	127,798	9.71	56,560
Alliance Sugar Mills	1,151,138	112,466	9.77	57,256
Ansari Sugar Mills	245,803	41,304	9.69	19,467

(continued)

Table 9.2 (continued)

Mill	Cane crushed (t)	Sugar production (t)	Recovery %	Molasses production (t)
Army Welfare Sugar Mills	348,531	36,308	10.42	16,780
Bawany Sugar Mills	188,456	19,000	10.08	8730
Bandi Sugar Mills	709,987	68,800	9.69	29,985
Chamber Sugar Mills	316,100	31,525	9.97	14,280
Deharki Sugar Mills	1,950,674	205,041	10.51	79,152
Dewan Sugar Mills	507,088	52,000	10.26	24,260
Digri Sugar Mills	471,261	47,468	10.07	23,478
Faran Sugar Mills	993,390	106,319	10.76	44,309
Gulf Sugar Mills	1,204,370	125,165	10.40	54,197
JDW Sugar Mills – III	2,016,687	207,747	10.30	81,210
Habib Sugar Mills	865,530	86,316	9.97	42,067
Khairpur Sugar Mills	852,226	83,579	9.80	33,237
Khoski Sugar Mills	236,399	23,047	9.75	11,080
Kiran Sugar Mills	408,718	36,417	8.91	18,392
Larr Sugar Mills	190,574	18,816	9.87	8,495
Matiari Sugar Mills	500,203	51,657	10.33	22,205
Mehran Sugar Mills	1,056,198	116,780	11.06	47,865
Mirpurkhas Sugar Mills	738,378	78,897	10.69	34,860
Mirza Sugar Mills	134,593	12,655	9.40	6,745
Najma Sugar Mills	Not operated			
Naudero Sugar Mills	268,019	26,405	9.85	10,965
New Dadu Sugar Mills	351,906	32,609	9.27	14,769
Pangrio Sugar Mills	Not operated			
Ranipur Sugar Mills	338,174	30,645	9.06	14,877
Sakrand Sugar Mills	459,573	42,300	9.20	19,500
Sanghar Sugar Mills	625,237	63,380	10.20	30,300
Seri Sugar Mills	9,650	573	6.00	434
Shahmurad Sugar Mills	672,747	72,755	10.8	30,750
Sindabadgar Sugar Mills	593,037	61,670	10.41	28,781
Tharparkar Sugar Mills	334,171	32,521	10.15	17,921
Tando Muhammad Khan Sugar Mills	Not operated			
Sanghar Sugar Mills	537,606	54,690	10.17	24,192
Tando Allahyar Sugar Mills	549,616	55,568	10.11	24,311

Source: PSMA (2017)

The indigenous resources of the country only fulfil 18% of the total demand of petroleum products (Tariq et al. 2014). Oil demands of Pakistan have steadily increased over time. Transport sector, alone, accounts for more than 50% of the domestic petroleum consumption (Tariq et al. 2014). Within the last 5 years, petroleum consumption has escalated to 589 thousand barrels per day (B D^{-1}) starting from 442 B D^{-1}. Petroleum products share as much as approximately 40% toward overall energy consumption of the country (British Petroleum Company plc 2018).

Table 9.3 Primary energy consumption of Pakistan by fuel type (million tons oil equivalent)

Reserves		Production			Consumption						
Natural gas	Coal	Natural gas	Coal	Electricity	Natural gas	Oil	Coal	Nuclear energy	Hydroelectricity	Renewable energy	Total primary energy consumption
Trillion cubic meters	Million tons	Billion cubic meters	Million tons oil equivalent	Terawatt-hours	Billion cubic meters	Million tons oil equivalent	Million tons oil equivalent	Million tons oil equivalent	Million tons oil equivalent	Million tons oil equivalent	Million tons oil equivalent
0.4	3064	34.7	1.8	123.9	40.7	29.2	7.1	1.8	7.0	0.8	80.9

British Petroleum Company plc (2018)

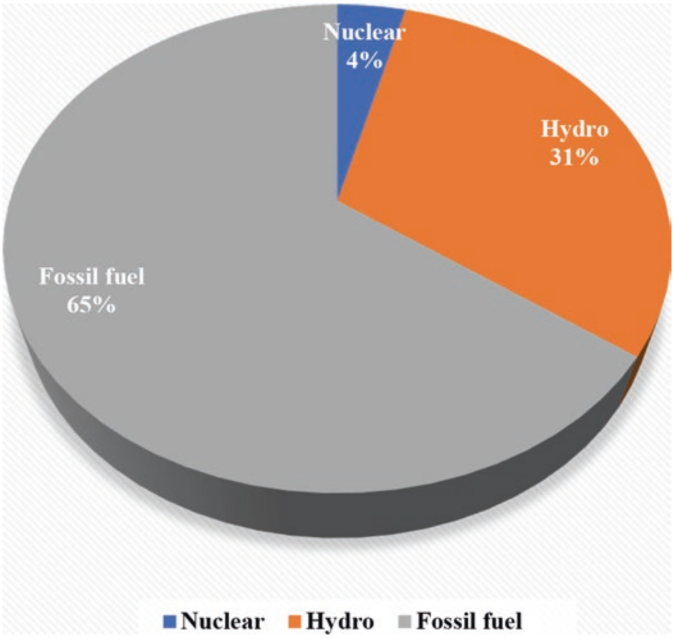

Fig. 9.4 Top three electricity sources of Pakistan. (Modified from Hussain et al. 2016)

Petroleum products are the greatest import of the country. Petroleum imports amplified by 30.5% year-on-year basis in 2017–2018. An import bill of $12.928 billion was recorded against $9.912 billion for the previous year. Regarding amounts spent on importing crude oil, a growth of 60.35% was observed as it costed the country ~$3.738 billion. However, keeping in view the imported quantity for the same, the growth was 28.72%, highlighting that the rise in import bills was more related to increase in international prices, depicting that Pakistan's economy is very much dependent on international oil prices (Arshad Hussain 2018).

Regarding electricity consumption of the country, Pakistan has a total installed capacity of 25,000 MW. Top three sources of electricity are fossil fuel, hydro, and nuclear (Fig. 9.4) (Hussain et al. 2016). Use of biomass, abundantly available in the country, has largely been underexploited. Supply and demand scenario of energy sector in Pakistan has remained extremely unbalanced for more than a decade. The country faced significant challenges in revamping its energy sector to fulfill the rising demands of power.

9.5 Sugarcane as a Fuel and Energy Source for Pakistan

Being one of the major cane producers of the world, Pakistan has a decent potential for producing cane-derived fuel and energy. Sugarcane is an excellent source of bioethanol as well as bioelectricity and can hence support energy needs of the country. Either first or second-generation ethanol can be obtained from sugarcane. The first-generation ethanol is produced from sucrose, cane juice, or molasses, whereas lignocellulosic biomass of the cane can be exploited for second-generation ethanol production. Ethanol, obtained from sugarcane, can be used as gasoline blend for consumption by vehicles (Khan et al. 2017a). Sugarcane bagasse, another byproduct in cane crushing, can be employed for electricity production (Khan 2018). Hence, molasses and bagasse are of great concern regarding cane energy production. Therefore, sugarcane can play important role toward petroleum fuels as well as power production (British Petroleum Company plc 2018).

9.5.1 Molasses Production in Pakistan

Molasses is the main source of ethanol in Pakistan. Ethanol can be utilized in fuel blending for economic and environmental reasons. Molasses production in Pakistan has gradually increased over time, attributed to rise in cane and sugar production and area under cane cultivation. Total molasses yield of Pakistan was 2.034 MT in 2011, which elevated to 3.077 MT in the year 2017 (PSMA 2017). Molasses and ethanol find applications in several domestic industries including pharma, food, cosmetics, and paper industry (Arifeen 2014).

Molasses is available in surplus amounts in Pakistan. The nation has been a major exporter of molasses to European Union (EU), Saudi Arabia, United Arab Emirates, and Afghanistan (Arifeen 2014). However, changes in import policies of EU have made molasses export to the region economically non-feasible. Consequently, Pakistan's export of molasses has greatly declined over time, in spite of increase in its production (Table 9.4). Pakistan recorded molasses export of 0.101 MT in 2017 as compared to 1.75 MT in 2000 (PSMA 2017).

Recognizing the advantages of employing molasses indigenously for various products rather than exporting it, Pakistan has imposed taxes on its export. As a result, domestic use of molasses in ethanol production has augmented in recent past. Ali et al. (2012) analyzed the ethanol production potential of Pakistan from molasses. Based on the ethanol recovery of around 240–270 l per ton of molasses, they projected that a total of two million tons of molasses (overall production at that time) could yield >0.6 MT of ethanol, which could be exported earning around $144 million. Pakistan's current molasses production is 3 MT, which can hence yield around 0.9 MT of ethanol as per their projection.

9.5.2 Bagasse Production

Bagasse is a leftover after juice and sugar extraction during sugarcane milling. It is residual dry fiber, which can be utilized for producing another form of bioenergy, i.e., bioelectricity. Bagasse is approximately fourth part of the cane, composed of

Table 9.4 Molasses production, exports, and export earnings of Pakistan (2010–2017)

Year	Production(Tons)				Exports (tons)	Value(million PKR)
	Punjab	Sindh	Khyber Pakhtunkhwa	Total		
2010–2011	1,249,324	643,651	141,580	2,034,457	86,437	892
2011–2012	1,445,830	624,956	153,583	2,224,369	55,608	577
2012–2013	1,422,807	663,305	166,639	2,252,751	225,221	2747
2013–2014	1,495,781	854,225	174,196	2,524,202	197,342	2510
2014–2015	1,281,767	781,665	183,702	2,247,137	83,229	1010
2015–2016	1,279,715	787,910	178,914	2,246,540	73,067	874
2016–2017	1,877,383	982,451	218,128	3,077,962	101,410	1217

Source: PSMA (2017)

50% cellulose, 25% hemicellulose, and 25% lignin (Rabelo et al. 2011). Sugar industry generally uses bagasse as a captive fuel for steam generation. Total calorific value of bagasse is around 2300 kcal kg^{-1} or 9731.984 kJ kg^{-1} (Arshad and Ahmed 2016; Sudhakar and Vijay 2013). High pressure boilers and special steam turbines are used by the sugar mills for electricity generation. By and large, one ton of bagasse produces 0.450 MWh of electricity (Arshad and Ahmed 2016).

Bagasse has huge potential for electricity generation. Bhattacharyya and Thang (2004) demonstrated that 3 kg of bagasse is needed for obtaining 1kWh of electricity through conventional technology. Moreover, Harijan et al. (2008) documented that 1 kWh electricity generation requires about 2 kg of bagasse. However, Purohit and Michaelowa (2007) illustrated that same amount of electricity can be produced only from 1.6 kg of bagasse.

Pakistan, a developing economy suffering from power crisis, is in urgent need of every possible route of adding power to the national grid. Electricity potential of bagasse in this regard is predicted to be around 1598–2894 GWh for the country (Arshad and Ahmed 2016). Sugar sector's potential for bagasse production and electricity generation from the same has been discussed in coming sections.

9.5.3 Trash and Tops

Sugarcane trash can also be utilized for energy production since it is a source of lignocellulosic materials (Pereira et al. 2015). Pakistan's sugarcane sector yields tons of trash every year which do not find appropriate applications. Cane trash and tops account for around 30% of the plant by weight, out of which 20% is shared by the tops. Although leaving trash in certain amounts is recommended for maintaining the land fertility, the quantity of trash available in fields is higher than what is required for this purpose. Hence, Pakistan can also employ the sugarcane leftovers for energy production (Aziz 2013). Keeping in view the current cane cultivation in

Table 9.5 Energy potential of cane trash available in Pakistan

Year	Cane production (MT)	Trash available[a] (MT)	Thermal energy available trash (GJ)	Power potential (GWH)
2015	62.652	6.265	41,976,840	11925.238
2016	65.482	6.548	43,872,940	12463.903
2017	75.482	7.548	50,572,940	14367.312

[a] Author's estimated values

Pakistan, the estimated available trash amounts to 7.548 MT. The projected thermal energy of this quantity of cane trash would be 50,572,940 GJ, which can offer a power potential of around 14,367 GWH per annum (Table 9.5).

9.6 Sugarcane Ethanol Production in Pakistan

Sugarcane is an excellent source of ethanol, which can be used as a transport fuel. Fuel ethanol is being produced in many of the cane-growing countries. Brazil, being a potential example in this regard, has extensively utilized sugarcane ethanol to fulfill its fuel demands. Ethanol can find applications as a stand-alone fuel or as a blend in gasoline in any ratio (Lisboa et al. 2011). For cane-producing countries like Pakistan, adoption of ethanol-blended fuel is a viable idea as it can help in decreasing the oil imports of the nation and provide environmental benefits.

Cane molasses is a cost-effective and abundantly available source of ethanol production. Industrial base for this feedstock already exists and is well-settled; however, the potential of molasses toward biofuel blending has remained untapped by now. Plentiful availability of molasses indicates that enhancing ethanol production in Pakistan will not affect the cultivation of other crops ensuring food security—the greatest concern against biofuels (Arifeen 2014).

Molasses' percentage from the crushed cane is around 4%, whereas the ethanol yields are up to 270 l per ton of molasses. Hence, as per current production of 3.08 MT of molasses, 770 million liters (ML) of ethanol can be produced (Arshad 2010; PSMA 2017). Pakistan is already producing surplus sugarcane, and the sugar industry of the country is continuously carrying-over the stocks of previous years (PSMA 2017). As of 2012, ~24.5 MT of sugarcane were available in excess after fulfilling the local demands of sugar. Subjecting this excess crop to ethanol for ethanol blending instead could yield up to 274 ML of ethanol. Considering the gasoline demand of 1435 MT for the same year, ethanol could substitute around 19.1% of annual gasoline consumption (Tariq et al. 2014).

Twenty-one distilleries are operating in the country having a capacity of two million tons of molasses processing, which can yield up to 400,000 tons of ethanol every year (Table 9.6). This amount is far higher than ethanol's current domestic applications, indicating that Pakistan does have surplus ethanol available for blending purposes (Ahmad et al. 2015; Arshad 2010). Arshad (2010) mentioned that

Table 9.6 List of distilleries and their installed capacities in Pakistan (2005–2006)

Name	Liters per day	Metric tons per year
Khazana Sugar Mills, Peshawar	23,000	4,600
Premier Sugar Mills & Distillery Co., Mardan	46,000	9200
Crystalline Chemical Industries (Pvt.) Ltd., Sargodha	100,000	20,000
CSK Distillers Ltd., Phalia	125,000	25,000
The Frontier Sugar Mills & Distillery Ltd., Takhat Bhai	14,000	2,800
Tandlianwala Sugar Mills Distillery, Faisalabad	125,000	25,000
Shakarganj-I – Jhang	160,000	32,000
Shakarganj-II – Jhang	100,000	20,000
Crescent Sugar Mills & Distillery Ltd., Faisalabad	22,000	4,400
Unicol, Mirpur Khas	100,000	20,000
United Ethanol, Sadiqabad	100,000	20,000
Haseeb Waqas Distillery, Nankana	125,000	25,000
Chishtia – Farooqia	100,000	20,000
Habib Sugar Mills Ltd. and Distillery, Nawab Shah	143,500	28,700
Al-Abbas Sugar Mills Distillery, Mirpur Khas	170,000	34,000
Matiari Distillery, Hyderabad	100,000	20,000
Dewan Distillery, Thatta	125,000	25,000
Shah Murad Distillery, Thatta	125,000	25,000
Murree Brewery, Rawalpindi	9000	1800
Pinnacle Distillery, Badin	125,000	25,000
Noon Sugar & Distillery, Bhalwal	80,000	16,000
Total	2,017,518	403,500

Modified from Khan et al. (2007)

Pakistan was producing 270,000 tons of ethanol per annum, in spite of its potential of around 400,000 tons year^{-1} in the mentioned year. Ahmad et al. (2015) reported the sum of ethanol demand of the country and exports to be around 80,200 tons, highlighting the possible availability of 318,000 tons of ethanol. Additionally, ethanol production in sugar mills also largely depends on the milling efficiency (fermentation, distillation, and dehydration processes). If milling efficiency of the sugar mills improves up to 47–48%, sugar industry may enhance ethanol production by 20–30% in Pakistan. On area basis, Eastwood (2011) suggested that 800 gallons of ethanol can be produced from one acre of sugarcane.

Ethanol can play three distinct roles in Pakistan. It can be used by domestic industries, can be exported abroad, and can be used for fuel blending. Pakistan's ethanol has majorly been exported, and its role in fuel blending has not been exploited well. Pakistan exports un-denatured ethyl alcohol and ethyl alcohol spirit (Table 9.7). The country has been the second largest exporter of ethanol to EU, following only Brazil. Moreover, Pakistani ethanol has also been exported to United

Table 9.7 Export of un-denatured ethanol

Year	Quantity (liter)	Value (PKR) (000)	Average price (PKR per liter)
2010–2011	168,509,200	9,506,883	56.00
2011–2012	215,814,894	14,234,428	65.96
2012–2013	142,065,426	835,649	61.49
2013–2014	492,476,805	32,168,695	65.21
2014–2015	421,881,994	25,749,257	61.00
2015–2016	396,940,741	22,929,248	58.00
2016–2017	358,483,301	29,330,083	82.00

Source: PSMA (2017)

Kingdom, China, and United States (Arifeen 2014). Tariq et al. (2014) analyzed the ethanol production capacity of Pakistan's sugar sector and projected that the country has potential to generate 274 ML of ethanol annually, without diverting the production of food products from cane crop.

Fuel grade ethanol needs to be ~99.8% pure. Molecular sieve technology can be employed for manufacturing fuel grade ethanol. In Pakistan, many of the sugar mills like Al-Abbas, Premier, Crescent, Habib, Colony, and Mehran have already installed their own distilleries. Moreover, eight distilleries have mounted the sieve technology for manufacturing fuel grade ethanol from the industrial alcohol (Khan et al. 2007). Unicol, a joint venture of three sugar mills, viz., Faran, Mehran, and Mirpur Khas sugar mills, has a capacity of producing 200,000 l of ethanol per day. This plant produces ethanol of up to 99.9% purity, apart from two other categories having >96%, and > 92% purity (Arifeen 2014).

Various ratios of ethanol can be implemented in Pakistan, keeping in view its production scenario. Tariq et al. (2014) designated E8 as the best possible blending rate for the country evaluating the ethanol production status of the country. The authors estimated that adopting this blend can reduce up to 0.5 MT of CO_2 emissions by the year 2030. However, it has been seen that startling rise in sugarcane production in recent years already surpassed their projection for ethanol engenderment and Pakistan's exports of ethanol rose up to 600 ML in 2017 (Fig. 9.5) (Agranet 2018). At current production rate, Pakistan has potential to attain up to 10% blending of ethanol.

Rise in ethanol production—if used for fuel blending—can help in saving huge foreign exchange by reducing country's petroleum import bills. Ethanol is a clean, low-carbon, and environmental-friendly fuel (Lisboa et al. 2011). Utilizing ethanol, or its blends in the energy sector, will not only benefit the country economically, but it will also contribute toward environmental commitments of the nation for reducing CO_2 emissions. Ethanol works as an oxygenate in fuel blends. It has 37% oxygen by weight which augments the octane rating of the fuel, leading to complete combustion and reduction in environmentally hazardous emissions (Tariq et al. 2014). Also, first-generation ethanol production from sugarcane is cost-competitive as the conventional technology used for the purpose does not require

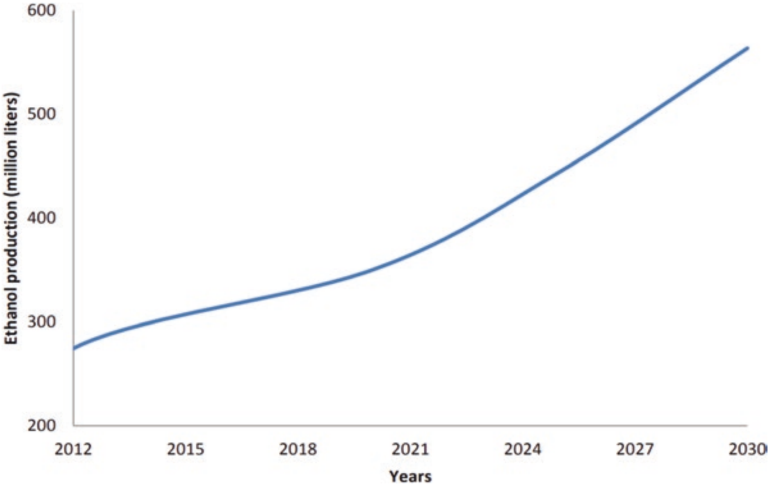

Fig. 9.5 Projection of ethanol production potential of Pakistan. (Source: Tariq et al. 2014)

expensive enzymatic pretreatments (Leal 2007). Furthermore, indigenous production of this fuel source will bring huge socioeconomic benefits to the local population by providing various direct and indirect jobs in cane production, sugar milling, and ethanol distillation.

For using ethanol in petroleum sector of the country, in 2006, Government of Pakistan directed the Pakistan State Oil (PSO) company to evaluate the performance of ethanol-blended fuel in selected cities. This was first attempt in the country for targeting biofuels adoption in future. After evaluation, PSO expanded its network of outlets providing E10 blends, and the marketing of blended fuel was also started in 2010. In order to promote adoption E10, economic incentives were also offered. However, till date, the venture did not progress majorly because of lack of coordination among involved stakeholders, improper planning and implementation, and no strict policies regarding blended fuels.

9.7 Sugarcane Bioenergy Production in Pakistan

Apart from being a source of ethanol-based biofuels, sugarcane sector can also provide bioelectricity. Cane bagasse, residual fiber collected after sugar extraction from sugarcane, can be employed for this purpose through cogeneration—the simultaneous production of heat and electricity (Naqvi et al. 2013; Kent 2010).

Sugarcane bagasse is widely employed for energy production in many countries such as Mauritius, Brazil, and India. Khoodaruth (2014) reported that sugarcane bagasse is contributing for 14% of electricity needs in Mauritius and its share is expected to increase up to 28% in recent future. Similarly, Ram and Banerjee (2003) illustrated that 3500 MW of electricity was being generated from sugarcane bagasse in India. Mbohwa (2003), and Mbohwa and Fukuda (2003) speculated that 210 MW can be obtained from bagasse cogeneration systems in Zimbabwe.

Bagasse has good potential for bioenergy production in Pakistan as country's power shortfalls, diminishing reserves of natural resources, environmental pollution, and economic disquiet have induced interests into renewable, sustainable, and environment-friendly sources of energy. Pakistan's total power generation capacity is 25,374 MW; 16,619 MW (65.50%) is shared by thermal sources, 7116 MW (28.04%) by hydroelectric, 787 MW (3.10%) by nuclear, and only 852 MW (3.36%) by renewable sources such as bagasse, wind, and solar (National Electric Power Regulatory Authority [NEPRA] 2016). The figures depict that bagasse has not been exploited to full capacity for energy production in the country.

Munir et al. (2004) reported that 11 kg of steam is needed to produce 1 kW of electricity and conservative boilers can generate 2.2 ton of steam from one ton of bagasse when 23 bars pressure is applied at 350 °C temperature. However, sophisticated modern pressure boilers can operate at 65 bar pressure with 510 °C temperature generating 2.40 tons of steam (Junqueira 2005). Hence, 1 kW of electricity can be cogenerated using only 5 kg of steam. A typical sugar mill processing 2000 tons of sugarcane has potential to generate 11 MW of electricity. Generally, requirements of such mills' own uses would be around 2 MW, and therefore, the rest (9 MW) can be sold to the grid. Hence, if this unexplored resource is utilized in Pakistan, up to 3000 MW of electrical energy can be added to the system through existing technology (PSMA 2016).

Interestingly, this 2000–3000 MWh of electricity by the sugar mills would be provided during the crushing season, which ranges from November to March every year. Pakistan suffers from extreme blackouts in same months because of reduction in hydropower production (PSMA 2016). Moreover, adopting the cogeneration technology at mills, 3613 MWh of electricity can be obtained. Electricity generation potential of Pakistani sugar mills through existing and cogeneration technology, as estimated by Arshad and Ahmed (2016), has been presented in Tables 9.8 and 9.9.

Shakarganj Mills Limited (SML) installed the first biogas-based electricity generation plant of the country in 2008. Faisalabad Electric Supply Company signed an agreement with the facility in the same year for inclusion into national grid. Pakistan was suffering from serious energy shortfall of 5000 MW in the said period, and such plant could contribute toward betterment of the situation by fulfilling the needs of 50,000 houses in the area where the mill is located. The plant uses Jenbacher gas engine which employs the extort from spent wash, collected during ethanol production from molasses, as feedstock. The capacity of the plant is 8.512 MW, and it has potential to cause 20,000 tons of certified emission reductions. Therefore, this project has been registered with United Nations Framework Convention on Climate Change (UNFCCC) by the Carbon Services Pakistan (DAWN 2008).

Table 9.8 Potential of electricity generation based on average cane crushed per day through existing technology

Year	No. of sugar mills	Sugarcane crushed (t)	Bagasse production (t)	Electricity production (MWh)	Electricity for mills' own needs (MWh)	Surplus electricity (MWh)
2008–2009	82	33,139,418	10,604,614	733	665	68
2009–2010	83	34,611,003	11,075,521	774	710	64
2010–2011	84	44,511,571	14,243,703	944	750	194
2011–2012	86	44,248,535	15,439,531	1023	800	223
2012–2013	86	50,089,483	16,028,635	1063	830	233
2013–2014	88	56,460,524	18,067,367	1369	840	529

Source: Arshad and Ahmed (2016)

Table 9.9 Potential of electricity generation based on average cane crushed per day through cogeneration technology

Year	No. of sugar Mills	Sugarcane crushed (t)	Bagasse production (t)	Electricity production (MWh)	Electricity for mills' own need (MWh)	Surplus electricity (MWh)
2008–2009	82	33,139,418	10,604,614	2121	665	1456
2009–2010	83	34,611,003	11,075,521	2215	710	1505
2010–2011	84	44,511,571	14,243,703	2849	750	2099
2011–2012	86	44,248,535	15,439,531	3088	800	2288
2012–2013	86	50,089,483	16,028,635	3206	830	2376
2013–2014	88	56,460,524	18,067,367	3613	840	2773

Source: Arshad and Ahmed (2016)

In February 2008, Al-Moiz industries situated at Dera Ismail Khan signed a conformity for electricity generation to supply up to 15 MW to national grid. The length of the agreement was 10 years, and the tariff was set at PKR 4.88 kWh^{-1}, together with bagasse fuel cost of PKR 3.62 kWh^{-1}. Later, Shakarganj Energy (Pvt.) Limited also initiated a bagasse-based isolated generation company having capacity of 31.50 MW. As of 2016, seven sugar units are exporting their excess electricity to the national grid in Pakistan, while four are in process.

Sugar mills are producing energy for their own use since 1990s. A renewable energy policy was launched by Pakistan in 2006. A list of bagasse-based power projects under said renewable policy is presented in Table 9.10, while Table 9.11 presented an overview of bagasse-based captive power producers. Most of the units are making use of Steam Turbine technology, as evident from the said tables. Energy production from cane is increasing in the country over time. A rise of 63 MW has been observed within a year (in 2015–2016). The overall input into National Transmission and Dispatch Company's system by the bagasse-based energy plants is 146 MW, summing their contribution to be 556 GWh (NEPRA 2016).

Table 9.10 Bagasse/Biomass power projects under renewable energy policy of 2006

S. No.	Name of Company and Location	Installed Capacity (MW)	Fuel Type	Technology
1	SSJD Bioenergy Limited, Mirpur Khas, Sindh	12.00	Bagasse	Bagasse
2	Lumen Energia (Pvt.) Limited, Jhang, Punjab	12.00	Biomass	ST[a]
3	Shakarganj Mills Limited-II, Jhang, Punjab	12.00	Bagasse +FO[b]	ST
4	Pak Ethanol (Pvt.) Limited, Tando Muhammad Khan, Sindh	9.132	Biogas	GT
5	JDW Sugar Mills Limited, Rahim Yar Khan, Punjab	26.35	Bagasse +Biomass	ST
6	JDW Sugar Mills Limited, Ghotki, Sindh	26.35	Bagasse +Biomass	ST
7	Chiniot Power Limited, Chiniot, Punjab	62.40	Bagasse	ST
8	RYK Mills Limited, Rahim Yar Khan, Punjab	30.00	Bagasse	ST
9	Hamza Sugar Mills Limited, Rahim Yar Khan, Punjab	15.00	Bagasse	ST
10	Alliance Sugar Mills (Pvt.) Limited, Ghotki, Sindh	30.00	Bagasse	ST
11	Ansari Powergen Company (Pvt.) Limited, Tando Muhammad Khan, Sindh	30.00	Bagasse	ST
12	TAY Powergen Company (Pvt.) Limited, Tando Allayar, Sindh	30.00	Bagasse	ST
13	Bandhi Powergen Company (Pvt.) Limited, Shaheed Benazirabad, Sindh	30.00	Bagasse	ST
14	Etihad Power Generation Limited, RYK, Punjab	74.40	Bagasse	ST
15	The Thal Industries Corporation Limited, Chiniot, Punjab	20.00	Bagasse	ST
16	The Thal Industries Corporation Limited, Layyah, Punjab	41.00	Bagasse	ST
17	Almoiz Industries Limited, Mianwali, Punjab	36.00	Bagasse	ST
	Total	496.63		

Source: NEPRA (2016)
[a] Steam Turbine
[b] Furnace Oil

9.8 National Policies

Pakistan's national policies, by now, have not focused much on adopting bioethanol or its blends. However, attempts have indeed been made to limited extent in the past.

In 2006, the Government of Pakistan initiated a pilot project by Alternate Energy Development Board (AEDB) for evaluating the use of E10 blend (10% ethanol +90% oil) in the country. The ethanol for the program was to be supplied by indig-

Table 9.11 Generation licensees: bagasse-based captive power producers

S. No.	Name of company and location	Installed capacity (MW)	Fuel type	Technology-wise capacity (MW)	
				Technology	Capacity
1	Shakarganj Sugar Mills Limited, Jhang, Punjab	8.512	Biogas	GT[a]	8.512
2	Almoiz Industries Limited, Dera Ismail Khan, Khyber Pakhtunkhwa	43.60	Bagasse + FO[b]	ST	43.60
3	Indus Sugar Mills Limited, Rajanpur, Punjab	11.00	Bagasse + FO	ST	11.00
4	Colony Mills Limited, Multan, Punjab	28.00	Bagasse + FO	ST	28.00
5	JDW Sugar Mills Limited, Rahim Yar Khan, Punjab	28.00	Bagasse + FO	ST	28.00
6	Brothers Sugar Mills Limited, Kasur, Punjab	13.00	Bagasse + FO	ST	13.00
7	Al-Noor Sugar Mills Limited, Shaheed Benazirabad, Sindh	36.80	Bagasse + FO	ST	36.80
8	RYK Mills Limited, Rahim Yar Khan, Punjab	18.00	Bagasse + FO	ST	18.00
9	Sheikhoo Sugar Mills Limited, Muzaffargarh, Punjab	18.00	Bagasse + FO	ST	12.00
10	Ashraf Sugar Mills Limited, Bahawalpur, Punjab	24.50	Bagasse + FO	ST	24.50
11	The Thal Industries Corporation Limited, Layyah, Punjab	30.70	Bagasse + FO	ST	30.70
12	Hamza Sugar Mills Limited, Rahim Yar Khan, Sindh	23.60	Bagasse + FO	ST	23.60
13	Eithad Sugar Mills Limited, Rahim Yar Khan, Punjab	22.00	Bagasse + FO	ST	22.00
14	Deharki Sugar Mills (Pvt.) Limited, Ghotki, Sindh	18.00	Bagasse + FO	ST	18.00
15	Tando Allayar Sugar Mills (Pvt.) Limited, Tano Allahyar, Sindh	12.00	Bagasse + FO	ST	12.00
16	Ittefaq Sugar Mills Limited, Pakpattan, Punjab	11.00	Bagasse + FO	ST	11.00
17	Digri Sugar Mills Limited, Mirpur Khan, Sindh	6.00	Bagasse + FO	ST	6.00
18	Fatima Sugar Mills Limited, Kot Addu, Punjab	120.00	Bagasse + FO	ST	120.00
19	Bandhi Sugar Mills (Pvt.) Limited, Shaheed Benazirabad, Sindh	12.00	Bagasse + FO	ST	12.00
20	Kamalia Sugar Mills Limited, Toba Tek Singh, Punjab	17.00	Bagasse + FO	ST	17.00
21	Ramzan Sugar Mills Limited, Chiniot, Punjab	12.00	Bagasse + FO	ST	12.00

(continued)

Table 9.11 (continued)

S. No.	Name of company and location	Installed capacity (MW)	Fuel type	Technology-wise capacity (MW)	
				Technology	Capacity
22	Noon Sugar Mills Limited, Sargodha, Punjab	14.80	Bagasse	ST	14.80
23	Fatima Energy Limited, Muzaffargarh, Punjab	120.00	Bagasse + Biomass	ST	120.00
24	Faran Sugar Mills Limited, Tando Muhammad Khan	13.00	Biomass + FO	ST	13.00
25	Chambar Sugar Mills (Pvt.) Limited, Tando Allahyar	5.00	Bagasse + FO	ST	5.00
26	Thal Industries Corporation Limited (for Safina Sugar Mills Limited – Plant I), Chiniot, Punjab	11.00	Bagasse	ST	11.00
27	Ranipur Sugar Mills (Pvt.) Limited, Khairpur, Sindh	25.50	Bagasse	ST	25.50
	Unicol Limited, Mirpur Khas, Sindh	6.60	Bagasse	ST	6.60
28	Alliance Sugar Mills (Pvt.) Limited, Ghotki, Sindh	13.50	Bagasse	ST	13.50
29	Habib Sugar Mills Limited, Benazirabad, Sindh	13.50	Bagasse	ST	13.50
30	Mehran Sugar Mills Limited, Tando Allahyar, Sindh	14.06	Bagasse	ST	14.06
31	Shahmurad Sugar Mills Limited, Thatta, Sindh	15.25	Bagasse	ST	15.25
32	Sanghar Sugar Mills Limited, Sanghar, Sindh	13.50	Bagasse	ST	13.50
33	Mirpurkhas Sugar Mills Limited, Mirpurkhas, Sindh	8.50	Bagasse	ST	8.50
34	Khairpur Sugar Mills Limited, Khairpur, Sindh	12.00	Bagasse + FO	ST	12.00
	Total	799.92			793.92

Source: NEPRA (2016)

[a] Gas Turbines

[b] Furnace Oil

[c] Steam Turbine

enous sources. Also, provincial governments were encouraged to enhance the blended fuel in the same year. The pilot project was launched in Islamabad by Pakistan State Oil (PSO), followed by opening of selected outlets in Karachi, and then Lahore. The program was conducted for half a year and 25 pre-identified vehicles using E10 blend were analyzed for performance (PSO 2006).

Pakistan Sugar Mills Association, in 2006, recommended that a 10% ethanol should be mandated through discussion with oil companies. They also suggested that substantial tax cuts should be offered for making operations for production of required quantities of ethanol possible, proposing the removal of GST as a major incentive in this regard. Later, in 2009, Economic Coordination Committee (ECC) permitted the E10 marketing on limited basis. The plan to manufacture E10-blended petrol was to be undertaken jointly by Ministry of Petroleum and Ministry of Industries and Production. ECC proposed that GST should be reduced, whereas petroleum levy should also be exempted. Later on, Petroleum Ministry proposed that PSO will initiate marketing E10 in 2010 in Karachi (Ali et al. 2012; PSO 2010).

In 2010, the E10 program was planned to be expanded to other cities including Rawalpindi, Sheikhupura, Gujranwala, Sialkot, Jhelum, and Mirpur Khas. The Oil and Gas Regulatory Authority (OGRA) fixed the price of E10 at PKR 62.61 per liter, which was less by PKR 2.5 per liter than the price of petrol at that time, to offer an economic incentive for promoting the blended fuel. Government also fixed 15% duty on export of molasses to encourage its domestic use in ethanol production, instead. Even the move to assess pure ethanol for public transport was under consideration. In 2010, PSO expanded the E10 availability at some outlets in Punjab province (Ali et al. 2012; PSO 2010).

In spite of significant efforts during 2006–2010, the policies did not remain consistent. Also, Pakistan aggressively initiated indigenous oil explorations. Investments in the petroleum sector were increased and several multinational companies are still conducting the oil reserves surveys in the country. Hence, till date, the E10 venture did not progress, majorly because of the lack of coordination among involved stakeholders and improper planning and implementation. On an optimistic side, renewable fuels projects are again being highlighted by the Government of Pakistan, and it can be hoped that role of renewable fuels, including cane ethanol, might increase in the coming years.

Pakistan has also suffered from extreme electricity crisis in the past decade and has explored various possible ways of energy extraction, including cane bagasse. J-tariff was launched by the government of Pakistan in 1990s for export of electricity from sugar industry to national grid on “as and when delivered” basis. However, only 4 MW of energy could be supplied. According to the tariff, sugar mills were supposed to bear the cost of interconnectivity, and in lieu of that, industry was allowed to adjust electricity consumption from the national grid. Some sugar mills acknowledged the tariff and connected their facilities with 11 kV grids. The tariff was set at PKR1.70 kWh^{-1} (for fuel cost only) and remained fixed for many years, leading to decline in interest of the sugar industry with the passage of time (Arshad and Ahmed 2016).

In 2002, new policy was formulated by the government which curtailed the industry benefits; as a result, electricity generation from sugar industry was reduced to very low level by 2007. The renewable policy of 2002 did not include biomass in its priorities of renewable energy sources. During the last 10 years, government has made many changes in the power generation policies, but no fruitful results were obtained (Mirjat et al. 2017). In 2007, the “National Policy for Power Co-Generation by Sugar Industry” was notified. In this policy, incentives were offered to the sugar industry to encourage mills to contribute toward power production. Purchase of power and payments for the same were guaranteed; moreover, tax cuts and concisions on import of technology were offered. Additionally, to address the investment issues, State Bank of Pakistan was requested to offer loans at lower interest rates of 6% for the renewable projects, instead of 12% (Khan 2018).

In 2012, a dynamic energy policy dealing with all sectors, i.e., bagasse, biomass, solar, and energy from waste, was introduced. The policy also introduced prominent financial and fiscal motivations to investors. Exceptional emphasis was put on the industries that could produce more than 50 MW of electricity. Moreover, prompt payment to energy producers was ensured. The said policy also encouraged independent power producer (IPP), which was adopted by many of the sugar mills. The tariff was linked with the natural gas prices, making it cost-effective for the industry. This policy also focused on development and initiation of the energy projects at a greater pace. Private Power and Infrastructure Board (PPIB) and NEPRA were directed to make decisions on such cases in a set time frame. Sugar mills, through this policy, were requested to complete the power projects within a period of 3 years, while NEPRA was advised to complete the feasibility report in a period of 1.5 months (Arshad and Ahmed 2016). NEPRA, in 2015, amended the upfront tariff approved in 2013, adjusting the new levelized tariff to PKR 10.7291 kWh^{-1} for bagasse-based cogeneration projects (NEPRA 2016, 2017).

Pakistan is still suffering from energy shortfall which becomes extreme in summers and when water reservoirs are low in winters. The winter period positions parallel to cane crushing season, suggesting that cane energy can help Pakistan tackle its blackouts when the hydropower production is low. Pakistan has still not explored the significant capacity of cane crop for adding energy to the grid, in spite of the fact that sugar industry's potential role in power production is very promising. Upgradation of technology at the sugar mills and higher incentives for bagasse-based IPPs can indeed enhance the industry's contribution toward energy sector of the country.

9.9 Advantages of Sugarcane-Based Fuels and Energy for Pakistan

The role of sugarcane sector in energy production is important for Pakistan for economic, social, and environmental reasons. As a source of biofuel, sugarcane-derived ethanol can significantly reduce country's oil imports, which are one of major burdens on economy. Transport sector of the country is the biggest consumer of imported petroleum, accounting for more than 50% (Arifeen 2018). Adopting ethanol-blended fuel in the country can substantially reduce the import burden of the country as this ethanol will come from indigenous crop source. Current molasses capacity of the country can meet the requirements for E10 blending, which does not require any amendment in vehicles' engines (Ali et al. 2012).

The energy demands of the country are expanding continuously, while the domestic reserves are limited. Sugar sector can help in overcoming the electricity shortage which has adversely affected the country for more than a decade. Power sector needs support from diverse sources so that uncertainty toward domestics use, business, and industrialization could be eliminated. Sugarcane sector has great potential for power generation, which can be enhanced even more by installing efficient power plants and high pressure boilers, replacing the conventional ones used currently (Valasai et al. 2017; Zuberi et al. 2013). Bagasse, a by-product of cane processing, can provide 3000 MW for national grid in current scenario (PSMA 2016).

Job creation is another important benefit Pakistan can achieve from adopting sugarcane biofuels and bioenergy. Being the second largest industry of the country, the sugar industry is spread across the country indicating that such jobs will be generated in rural and economically deprived areas of the state—giving this strategy a unique edge over oil imports for the purpose which does not provide socioeconomic opportunities. Such jobs will not only be created in mills and distilleries for skilled and non-skilled workers, but farmers and labor involved in cane production in the country will also benefit. Moreover, sugarcane production will return higher profits, enhancing the livelihood of rural communities involved in cane production (Arshad and Ahmed 2016).

Bagasse electricity production is also important because of the fact that it does not only limit the use of fossil fuels for power generation, but also reduces the impacts of sugar mills on environment by decreasing amounts of environmentally hazardous materials disposed of otherwise. Natural decay of bagasse generates methane gas, which impacts the ozone layer negatively (Janke et al. 2015). Pakistan is among the list of countries which are most vulnerable to the climate change. Hence, global, as well as internal, attempts to mitigate climate change are extremely important for the country (Khan et al. 2016). Furthermore, cane ethanol blending also cuts the carbon monoxide and hydrocarbons' exhaust as an advantage toward environmental aspects (Goldemberg et al. 2008).

Air pollution in Pakistan is several times high as compared to the international recommended standards. The life cycle analysis of well to wheels for ethanol has shown that ethanol has least CO_2 emissions among the transport fuels. Moreover, octane number of ethanol is 120, while, on the other hand, that of petrol is around 108.6, suggesting that ethanol blends can enhance the octane number of the fuel mitigating the use of hazardous substances like methyl tertiary butyl ether (MTBE). Therefore, adopting ethanol-based biofuels can help Pakistan limit greenhouse gases' (GHG) emissions as well (Arshad 2010; Shahad et al. 2008).

9.10 Limitations and Challenges

In spite of being a huge importer of petroleum on one hand, and a substantial producer of cane ethanol on the other, no significant use of fuel blending highlights the shortcomings at policy level. Absence of mandatory blending requirements at national level has limited the use of ethanol in fuel sector. Consistent policies and strict implementation are necessary for launching and adoption of ethanol-blended fuel. Proper marketing to build trust in the drivers for new fuel type is another challenge. Moreover, such blends need also to be provided at lower costs, so that the consumers could prioritize opting for blended fuel (Ali et al. 2012).

Financial reasons have been the greatest hindrance for mills to progress toward cane fuel and energy production. Upgradation of technology at distilleries and mills' boilers is necessary for Pakistan's case to enhance the efficiency and production capacity of such projects. However, the payback period of these huge investments is long, making the investors reluctant to involve in such programs. Low profit loans must be provided to encourage investments in this sector.

Regarding power production, government and mills have differed on tariff issues as the mills demanded higher tariffs keeping in view the large investments required in upgrading their boilers. Duration for launching the project, fuel availability, technical hurdles, and necessity of using demineralized water put barrier toward this industry. Also, remote location of mills, although an advantage from certain aspects, necessitates infrastructure development in some cases. Costs of connecting with the grid lines also represses the export of surplus energy to the national grid (Arshad and Ahmed 2016).

Challenges exist at the level of cane farming as well. Per hectare yield of the country is low as compared to many of the other cane-growing countries. Being a perennial and water-loving crop, sugarcane requires intensive agronomic practices for obtaining high cane yield and sugar recovery. Unapproved varieties are being planted, while other factors like limited irrigation resources, lack of technology adoption, irregular use of fertilizers, and poor management practices also introduce issues at cane production level. (Buzacott 1965; Dunckelman and Legendre 1982; Haq et al. 1974).

9.11 Future Perspectives

In spite of increase in local production and imports of oil and liquefied natural gas, Pakistan does not have enough supplies of energy to meet its demands. Power breakdowns happen routinely, especially when water reservoirs are low; CNG for transport sectors is available only on limited days; and gas supplies for domestic consumption are also not enough to satisfy the requirements. Thus, Pakistan needs to explore new possible routes of energy extraction for meeting the supply and demand gaps, which is expected to enhance renewable sources' (including sugarcane) role in energy matrix of the country.

Moreover, Pakistan is a signatory to various international environmental commitments and is one of the most actively involved countries of the world in mitigating climate change. Therefore, the country is anticipated to exploit renewable sources of energy for environmental reasons as well. Pakistan has recently completed Billion Trees Project in one of its provinces and is now on its way to planting 10 billion trees—showing the commitments of the nation to combat climate change (Constable 2018). Projects employing renewable energy in transport sector have already been planned for country's largest and highly populated city, i.e., Karachi. Hence, it can be expected that the national priorities are set to increase the renewable fuels' usage in the country.

Energy security and lower dependence on imported gasoline are other incentives ethanol fuels can offer. Having huge quantities of molasses available, and already well-set sugar industry, it can be estimated on an optimistic approach that ethanol may find applications for blending purposes in future. Ethanol blends can offer several advantages like reduction in air pollution and lower GHG emissions, complete burning of fuel, and the cuts in CO_2 emissions. Moreover, ethanol blends in the country can provide higher economic returns to distilleries against its exports. Hence, it can become a priority fuel of the country in coming years (Arifeen 2014).

Several measures can be helpful in enhancing sugarcane's role in bioenergy sector of Pakistan. Imposing higher taxes on molasses' export, and removing the same on industrial alcohol for boosting its production, can help. Financial support toward power plants and distilleries is another essentiality. Moreover, blending mandates need to be launched for ensuring sustainability toward ethanol fuel production. PSO can play significant role in marketing and expanding blended fuel availability.

9.12 Conclusion

Ethanol's role has remained limited in Pakistan's energy matrix. Attempts to enhance its position as a fuel blend have not produced significant results because of lack of planning and implementation in this multi-stakeholders sector. Nevertheless, keeping in view the availability of molasses, current economic scenario of the country, and its commitment toward climatic and socioeconomic goals, it can be anticipated that sugarcane bioethanol may be emphasized again in upcoming polices. The scope of sugarcane-based cogeneration of bioelectricity also holds great potential to tackle the electricity deficit in Pakistan; however, this phenomenon also has remained largely underexploited. Changing national policies and the insecurity of the investors are major reasons in this regard. Some of the mills are already supplying the cogenerated electricity to national grid; however, many others may follow if better incentives and economic support are offered. Pakistan is suffering from energy shortage, and therefore, renewable sources like sugarcane can contribute significantly toward ethanol-blended fuels as well as cogenerated electricity for the country.

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Chapter 10
Ethanol Production from the Mexican Sugar Industry: Perspectives and Challenges

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10.1 Introduction

Sugarcane is one of the major crop commodities of the world. It has initially been used for sugar production all around the globe; however, its potential as a fuel and energy source, and for various other products of economic importance, has increased over time (Khan et al. 2017). The combined engenderment of sugar and bioethanol from cane is a viable system to increase the competitiveness of mills in this agribusiness.

Bioethanol is a renewable transport fuel from the millennial biotechnology process of fermentation. Some bioethanol-based fuels programs are E5 (UK), E10 (EU), E15 (United States of America), and E25-100 (Brazil). Molasses is one of the most established feedstocks for ethanol production, contributing about 32 % of the world biofuels (Licht's 2017). Yet, sugarcane has not been used to its full potential for bioenergy in many countries, including Mexico. Several fallow wastes are generated, and the efficiencies of extracting energy contents of the bagasse, and especially the trash, are low. In spite of advancements in fermentation, pretreatment operations, and ethanol chemistry, there is still considerable room for improvement (Fig. 10.1).

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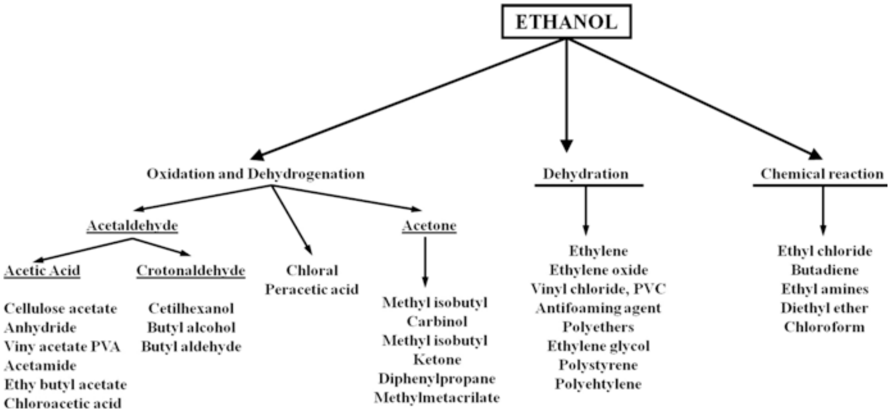


Fig. 10.1 Ethanol chemistry. (Modified from Gálvez et al. 2000; Maity 2015)

Sugarcane is one of the main crops of Mexico. The cultivation of sugarcane, as raw material, is important for Mexico in terms of acreage and jobs created as well. Approximately 184,000 Mexican growers are involved in sugarcane cultivation. The sucrose market also has various types of related interests involving soft drinks production units and bakery and confectionery industries.

10.2 Mexican Sugar Industry: Status, Products, and Economics

Mexico is world's tenth largest producer of sugar from sugarcane, which is cultivated at around 783,515 ha, producing over 53.3 million tons of crop. The Mexican sugar industry yielded 5.95 Mt of sugar and 13.8 million liters (Ml) of ethanol in the 2016/2017 harvest season. The sugar fraction was constituted by 3.8 Mt raw, 1.6 Mt refined, 0.26 Mt white, and 0.26 Mt muscovado sugar (National Chamber of the Sugar and Alcohol Industry [CNIAA] 2018). Mexico is self-sufficient in sugar and a modest exporter to various countries, United States being the main buyer within the North American Free Trade Agreement (NAFTA) (Figs. 10.2 and 10.3).

There are 51 sugar mills operating in the country. The mills are owned by 17 sugar groups called Beta San Miguel, Zucarmex, PIASA, Santos, Grupo Azucarero México, Porres, Sáenz, La Margarita, Grupo Azucarero del Trópico, Pantaleón, Motzorongo, Puga, Menchaca, Fanjul, Perno, Grupo González, and Jiménez Sainz. Beta San Miguel and Zucarmex belong to "The One Million Tonnes Sugar Club."

The Mexican sugar industry is characterized as having medium to low productivity because of high acreage and heterogeneous yields in the field and factories (Sentíes-Herrera et al. 2017). The sugar mills are located in 15 states, namely, Veracruz, Jalisco, San Luis Potosí, Oaxaca, Chiapas, Nayarit, Tabasco, Morelos,

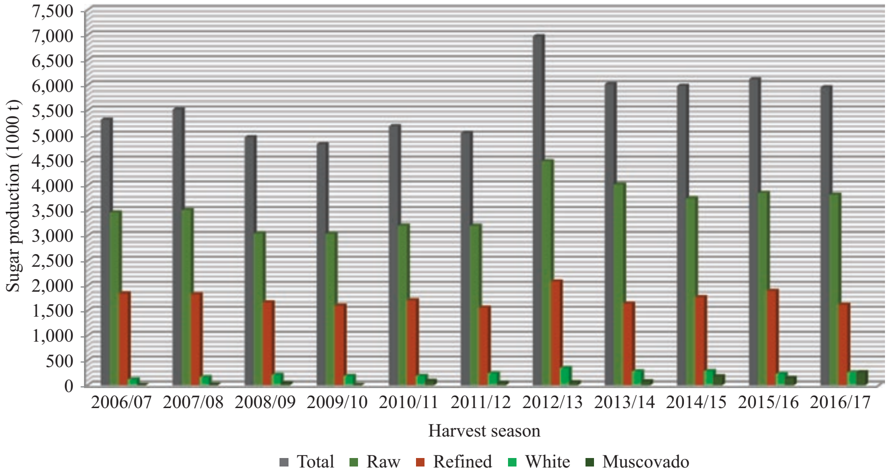


Fig. 10.2 Mexican sugar industry's production by type of sugar. (National Committee for the Sustainable Development of Sugarcane [CONADESUCA] 2017)

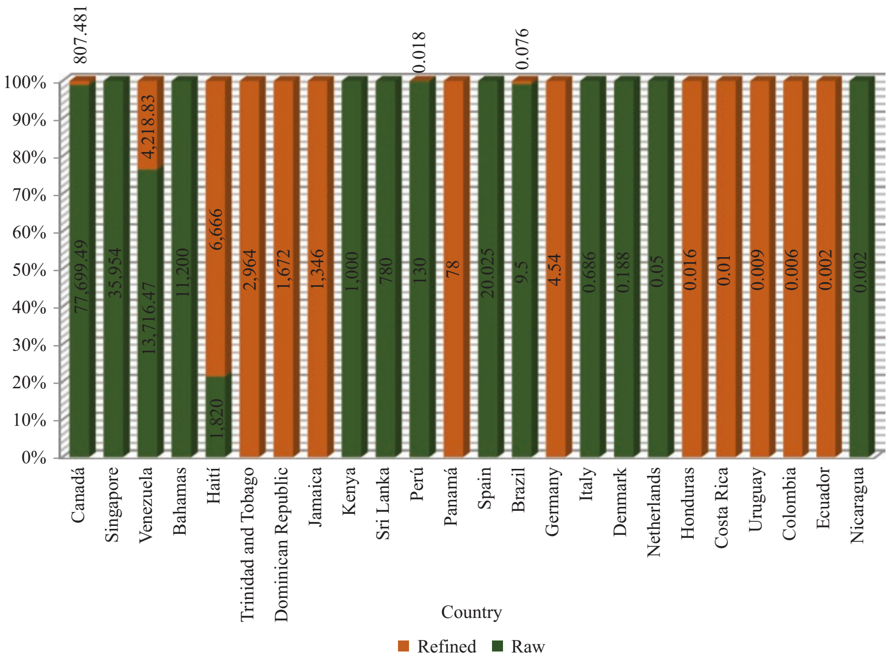


Fig. 10.3 Mexican sugar exports. (CONADESUCA 2017)

Puebla, Tamaulipas, Quintana Roo, Colima, Michoacán, Campeche, and Sinaloa, and spread over seven Administrative Regions (Center, Cordoba-Gulf, Northeast, Northwest, Pacific, Papaloapan-Gulf, and Southeast). The states of Veracruz, Jalisco, and San Luis Potosí alone account for 61.5 % of the domestic sugar in Mexico. Six sugar mills have stopped operating because of various technical and economic problems in previous years (Aguilar-Rivera et al. 2018) (Fig. 10.4).

The southeastern and mid-western regions are characterized as high sugarcane yield-producing areas. Mills in these regions have competitiveness because of added value cane bagasse with off-season electricity generation and ethanol production. The highest productivity has been recorded at the Atencingo and Central Casasano sugar mills located in Morelos with 110.04 and 109.9 t ha^{-1} yields, respectively. Many of the mills in other areas are running less efficiently, mainly because of the facility ageing, poor operating procedures, and the heterogeneous quality of the sugarcane crushed. The lowest productivity has been seen at Azsuremex, having a production of 45.47 t ha^{-1} year^{-1} cane crushed (CNIAA 2018) (Figs. 10.5, 10.6, 10.7, 10.8, 10.9, 10.10, and 10.11).

The variability in the production of sugarcane fields in relation to average sugarcane (t) and acreage (ha) to produce one ton of sugar in Mexico (8.95 t cane and 0.13 ha) depends on multiple factors, including differences between agroclimatic conditions, management practices, and the crop varieties. Although the national average yield is very low, i.e., 68 t ha^{-1}, notwithstanding, the sugarcane regions in Mexico have important comparative advantages regarding soil types and climatic conditions to become more competitive, as one of the most viable strategies to increase the sugar industry's efficiency is to increase the productivity in crop fields.

The output of a Mexican sugar mill depends on the supply of sugarcane and capital goods, land, technology, and government legislation. The main products (sugar, ethanol, and energy) are sold to distributors, the food industry, retailers, exporters, and the public electrical grid. By-products are destined to other industries, wholesalers, and retailers of other sectors such as the animal feed and food industry, or for exportation. In addition, sugarcane mills use, or trade, residues such as vinasses and cake filter as biofertilizers (Fig. 10.12).

Sugarcane sector has huge potential for Mexico. However, since the introduction of sugarcane by Hernan Cortes and the Spanish conquistadors, the establishment of sugar mills has been carried out for sugar production alone. There are numerous competitive and sustainable production schemes and business opportunities, which still have not been exploited by the Mexican industry. The biorefinery concept can increase the profitability of mills and competitiveness of sugarcane as a commodity in the country. Figure. 10.13 enlists some of the business opportunities available for the industry, and the hurdles which need to be tackled, for adoption of all these concepts at industrial level.

Fig. 10.4 Sugar mills in Mexico. (CONADESUCA 2017; CNIAA 2018)

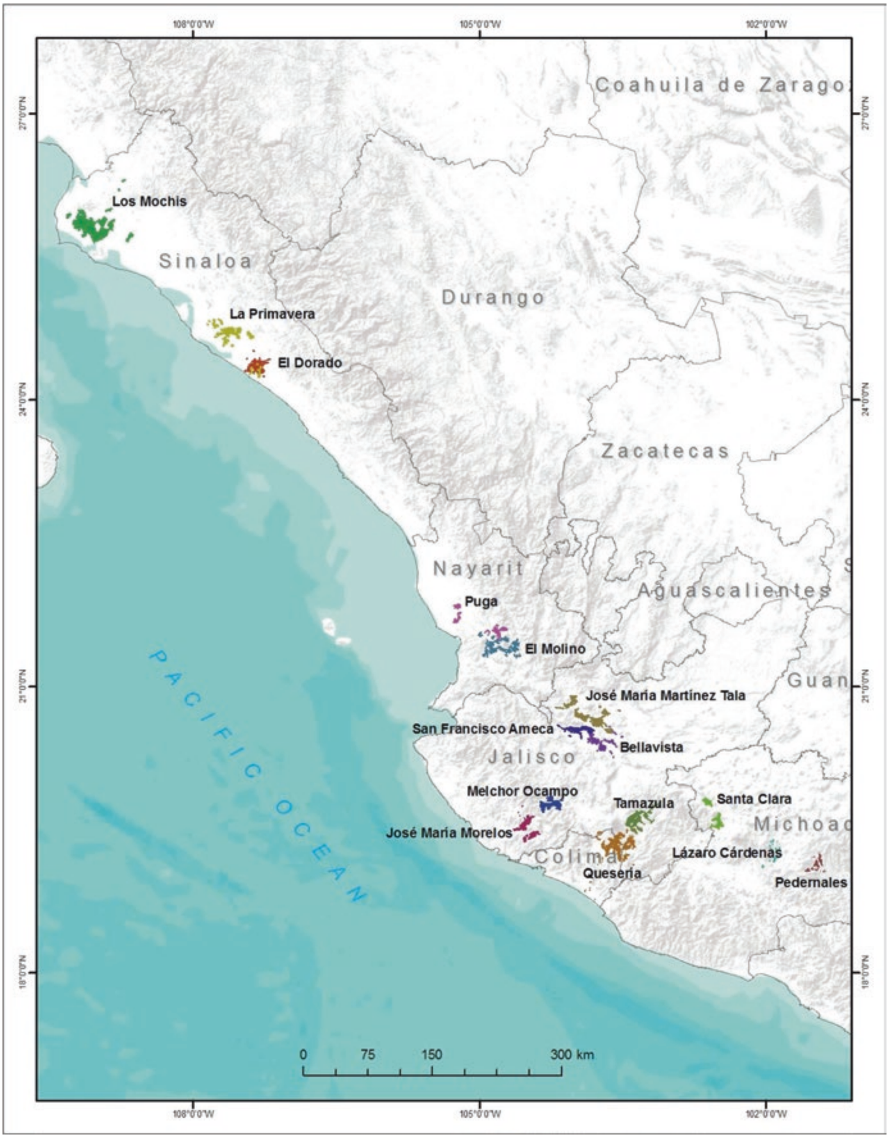


Fig. 10.5 Sugarcane supply zones for sugar mills of Northwest and Pacific region (Michoacán, Colima, Jalisco, and Nayarit states). (CONADESUCA 2018)

10.3 Ethanol as a Product of Mexican Sugar Industry

The production of biofuel from sugarcane has several technical advantages. It can be generated using the whole of the sugarcane plant, juice, syrup, and the by-products resulting from sugar processing such as intermediate and final juices and

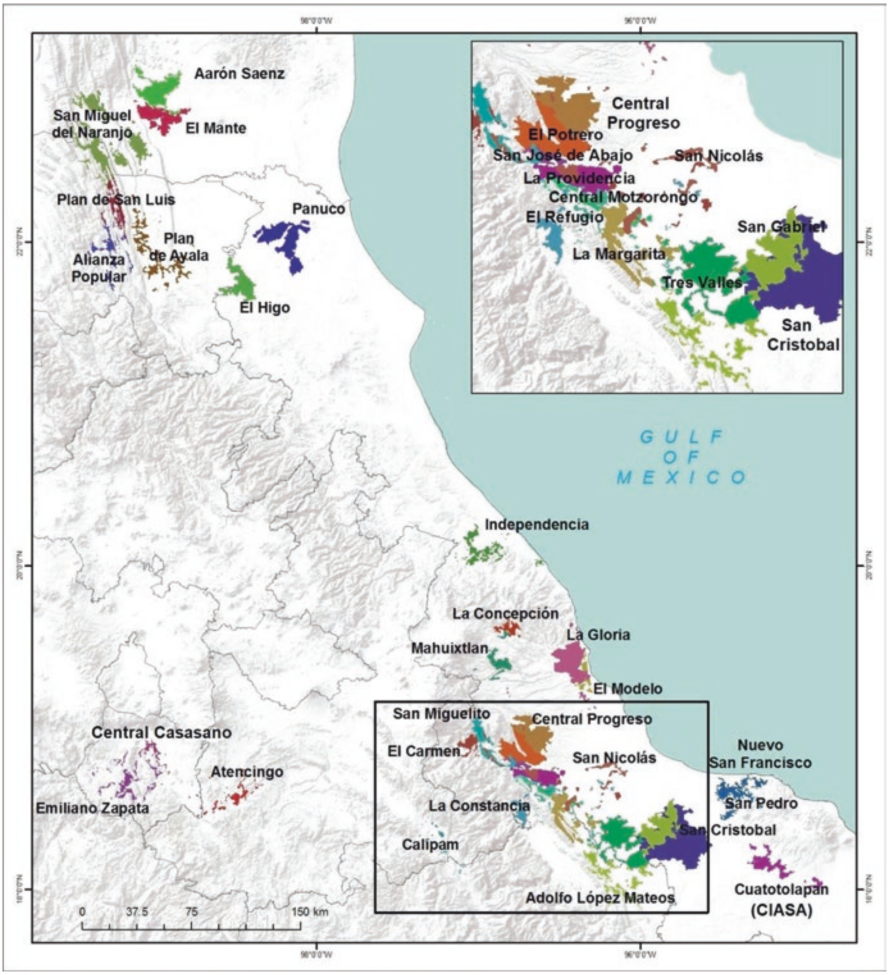


Fig. 10.6 Sugarcane supply zones for sugar mills of Center, Cordoba-Gulf, Northeast, and Papaloapan-Gulf regions (San Luis Potosi, Tamaulipas, Morelos, Puebla, Oaxaca y Veracruz states). (CONADESUCA 2018)

molasses according to the available technology and the markets. Bioethanol can be considered as an inexhaustible source of biofuel since it is obtained from plant material. Apart from finding applications in fuel and energy sector, it can also be used by the chemical industry for production of esters, organic compounds, detergents, cosmetics, paints, aerosols, soaps, and perfumes, among other items (Aguilar-Rivera 2007).

The production of ethanol in distilleries annexed to sugar mills is marginal in Mexico. Of the total number of sugar mills, only five produced ethanol in the season 2016/2017. Developing a biofuel market involves various stakeholders, viz., growers, sugar mills, distilleries, vehicle manufacturers, transport sector, and the govern-

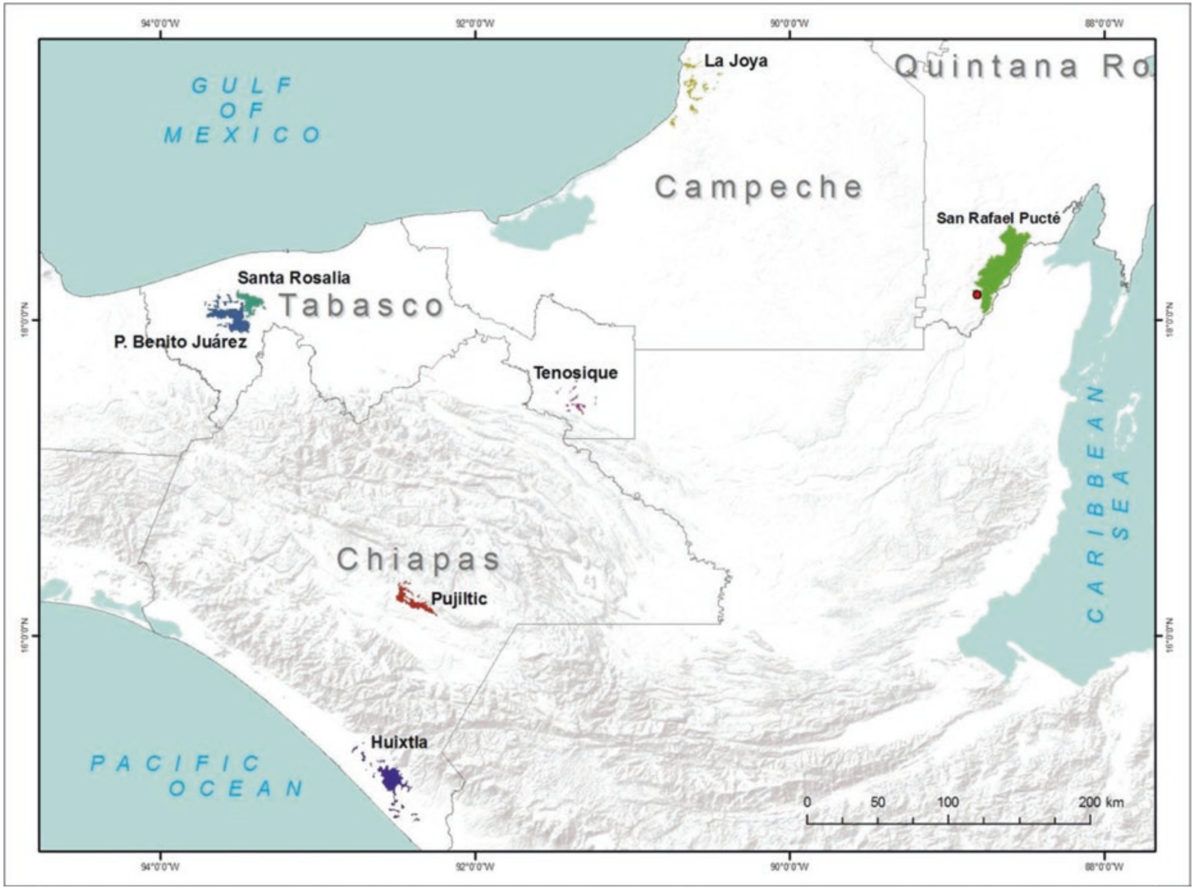


Fig. 10.7 Sugarcane supply zones for sugar mills of Southeast region (Tabasco, Chiapas, Campeche, and Quintana Roo States). (CONADESUCA 2018)

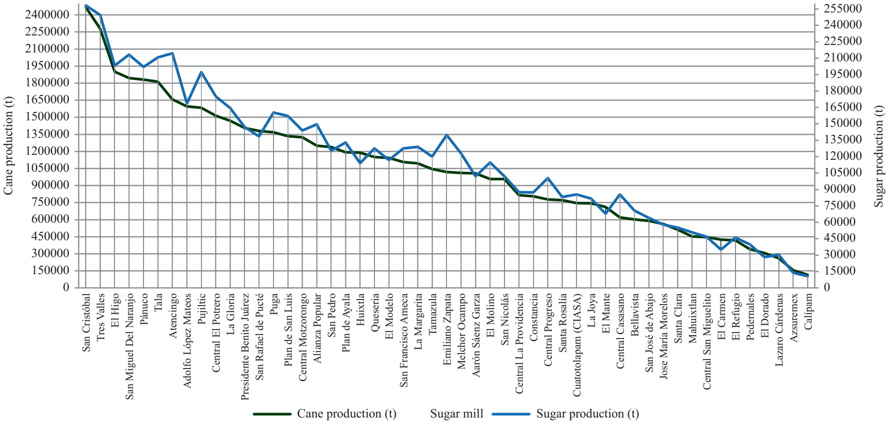


Fig. 10.8 Production of sugarcane and sucrose in Mexico in 2016/2017 harvest season. (CONADESUCA 2017)

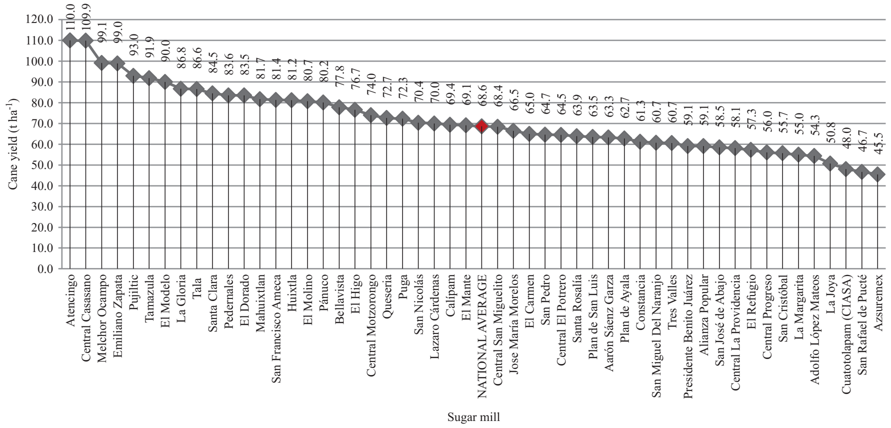


Fig. 10.9 Sugarcane yield (t ha^{-1}) in harvest season 2016/2017. (CONADESUCA 2017)

ment. Therefore, a national program for producing ethanol from sugarcane has been identified as the major starting point. Any such program should aim for socioeconomic and environmental targets, not only technological ones. In addition, it is necessary to emphasize that Mexico is a producer and exporter of oil, but net importer of gasoline and petrochemicals, which highlights the role of corporate culture and hints toward a significant constraint against competitive ethanol production in the country (Elizondo and Boyd 2017). (Figure 10.14).

Lora et al. (2014a, b) discussed the major technological changes needed for the implementation of large-scale cogeneration and biofuel production in conventional sugar and alcohol industry. They suggested that improvements in steam consumption in milling, installation of new hydrolysis and gasification technologies, and

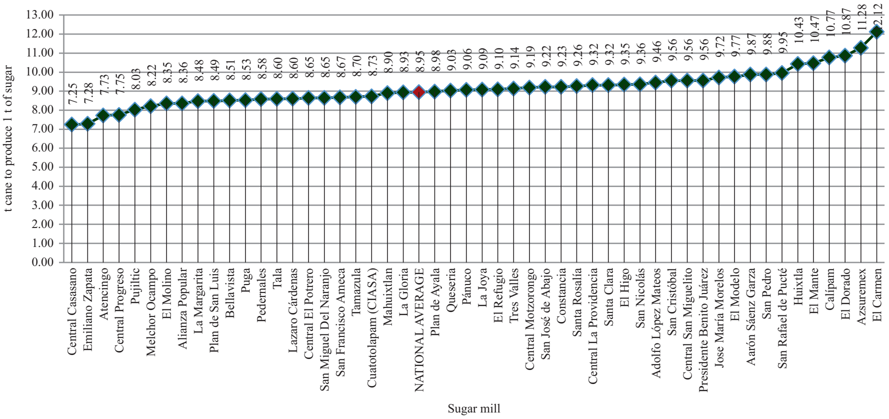


Fig. 10.10 Raw material (t) used to produce one ton of sugar in harvest season 2016/2017. (CONADESUCA 2017)

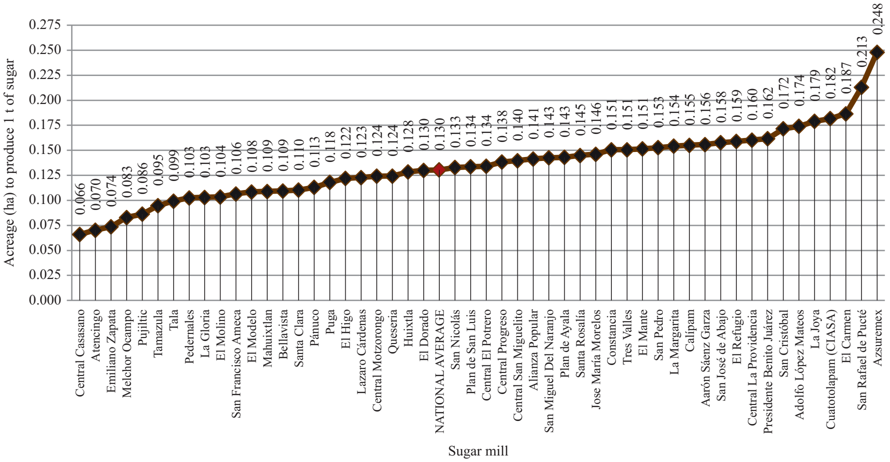


Fig. 10.11 Harvested area (ha) to produce one ton of sugar during harvest season 2016/2017. (CONADESUCA 2017)

proper utilization of sugarcane trash and vinasse can help the process of integration and implementation of biorefinery concept making the milling for bioethanol more cost-effective. They also concluded that investments in research, development, and innovation (RD & I) are essential to enable new ethanol projects to be lucrative. In general, the RD & I investments can lead to development of new sugarcane varieties, greater agricultural and industrial yields, and soil management techniques tailored to the agroecological conditions. Investments in RD & I can favor greater agricultural efficiency, whereas the modern approaches of genetic engineering can significantly enhance sugar and biomass availability.

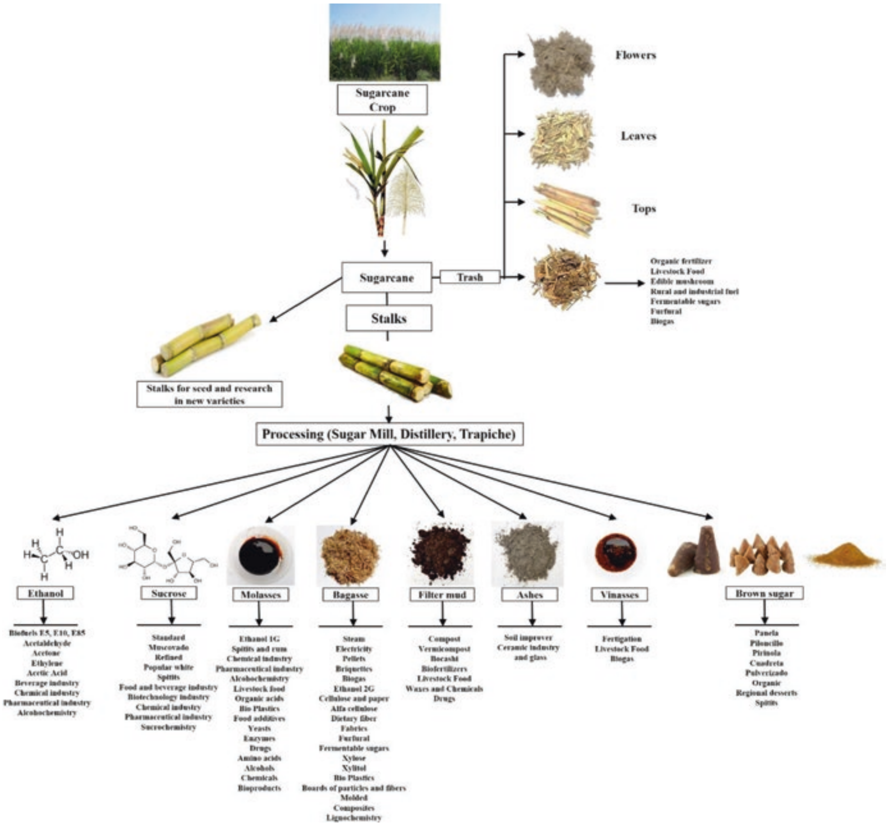


Fig. 10.12 Various products and by-products from sugarcane. (Modified from Aguilar-Rivera 2017)

However, in Mexico, there is still considerable uncertainty throughout the value chain because of unstable sugarcane yields in various regions, heterogeneous processing technologies in sugar mills, high fuel and water consumption in cane processing, and the energy market that ignores the effects of ethanol fuel use on vehicle emissions and environmental benefits. Therefore, even in Mexico City, Monterrey, and Guadalajara (the largest cities in the country with substantial automobile-generated environmental pollution problems), there is hesitation about the adoption of bioethanol fuels. Although it is recognized that ethanol fuels can help mitigate GHG emissions, changes required in vehicle engines for the purpose discourage the consumers (Alvim et al. 2017). Conventional vehicles do not support high levels of ethanol; to minimize the adverse effects of using higher levels of ethanol, combustion and emission control systems need to be optimized for blended fuel. Furthermore, role of Mexican research bodies is also expected to have limited impact on country's legislation and strategic direction to lessen the dependence on gasoline for environmental and social reasons (Gracida Rodríguez and Pérez-Díaz

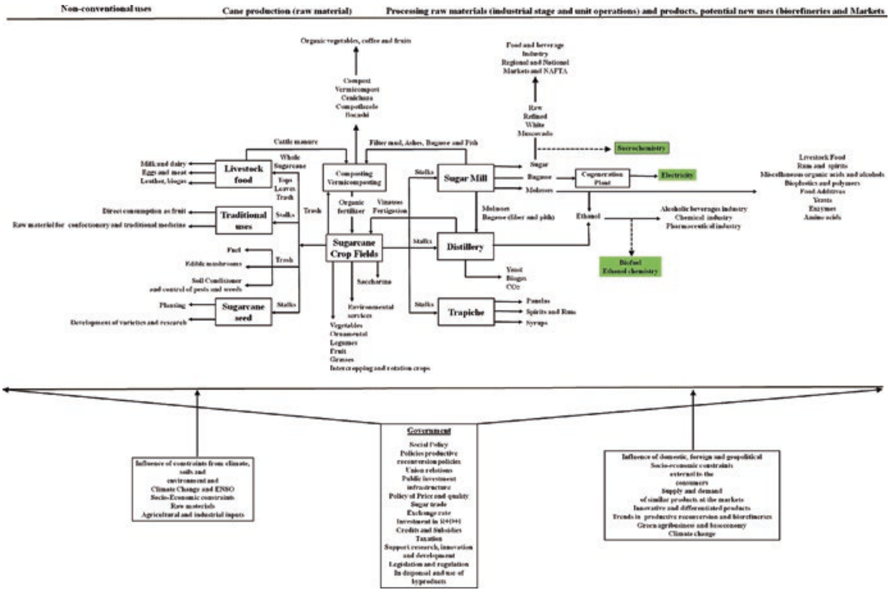


Fig. 10.13 Business opportunities and the associated constraints for sugarcane sector in Mexico. (Sentíes-Herrera et al. 2017)

2014). It is anticipated that biofuel usage will increase in the urban zones in some years; however, to a limited extent, that is unlikely to significantly improve the air quality in such areas (Ruiz et al. 2016).

In spite of the hurdles, keeping in view current production capacity and distilling technologies available, only sugarcane industry can generate enough supplies to target ethanol blending in Mexico. García et al. (2017) reported that, currently, imports account for 48% of the country's overall gasoline consumption. Thus, the price of gasoline in Mexico is dependent on the exchange rate and international oil geopolitics. Adopting ethanol blends can help Mexico reduce its gasoline imports and assist in saving foreign exchange and ensuring energy security. For achieving this goal, the Mexican sugar industry needs to maximize the bioethanol yields of sugarcane, minimize the energy consumption by the sugar and ethanol mills, and maximize surplus electricity production through process and technological improvements.

10.4 Gasoline Resources of Mexico: In a Perspective to Ethanol Fuels

Mexico ranks among the top 10 oil producers worldwide. Oil reserves allow it to be a net exporter of the primary energy; however, for its secondary energy's needs, the country is a major importer of liquefied gas, natural gas, petroleum coke, coal, gasoline, and naphtha (Becerra 2009). According to data provided by the Energy

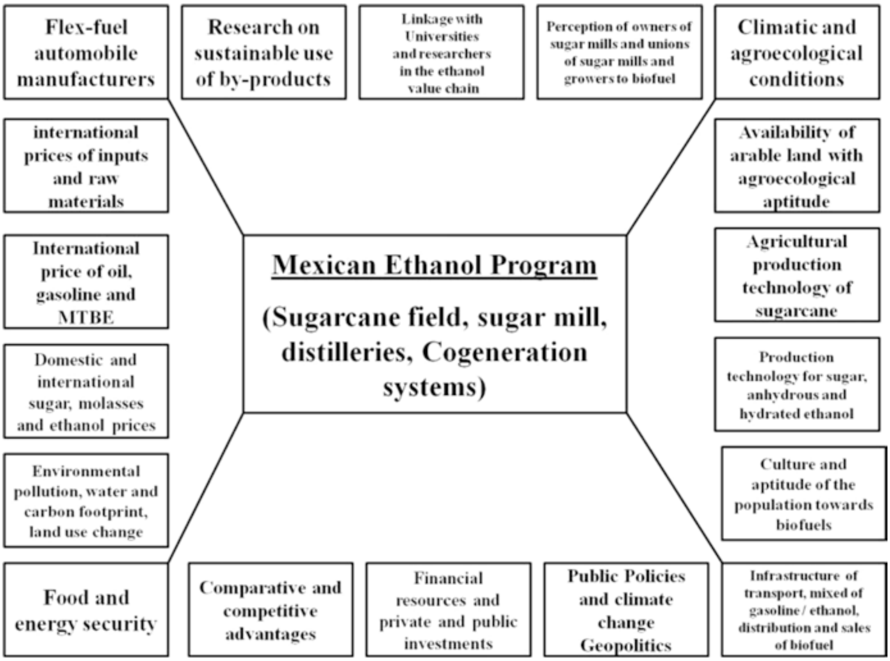


Fig. 10.14 Constraints and challenges for competitive ethanol fuel program in Mexico. (Aguilar-Rivera et al. 2017; de Man and German 2017)

Information System (SIE for its initials in Spanish) of the Mexican Energy Secretariat, Petróleos Mexicanos (PEMEX; state-owned oil and gas company) is a net crude oil exporter (Maya, Olmeca, and Istmo); however, it does not have the capacity to produce the gasoline that is currently demanded at the national level. Therefore, to satisfy domestic fuel demands, it imports gasoline from different countries.

Figures 10.15 and 10.16 show the behavior of the volume of PEMEX-produced gasoline, the volume of gasoline imported, and the volume of gasoline sold by Mexican gas stations in the period from 2012 to 2018 (October). Data are presented in thousands of barrels per day with monthly average.

Unfortunately, PEMEX does not have the necessary infrastructure for refining petroleum products; therefore, gasoline has to be imported to satisfy the domestic demands of the country. The volume of imported gasoline is considerable; in 2012, 50% of gasoline sold in Mexico was of foreign origin. As of October 2018, about 80% of the gasoline consumed in Mexico was imported.

Mexico has significantly invested on PEMEX's infrastructure as well as reforms in energy sector for crude oil extraction (González-López and Giampietro 2018; Vietor and Sheldahl-Thomason 2017). However, the volume of gasoline produced in the refineries, Salamanca, Tula, Madero, Cadereyta, Salina Cruz, and Minatitlán, has decreased since 2013 to date. Furthermore, the price of gasoline has also increased significantly since December 2016, because of the increase in international

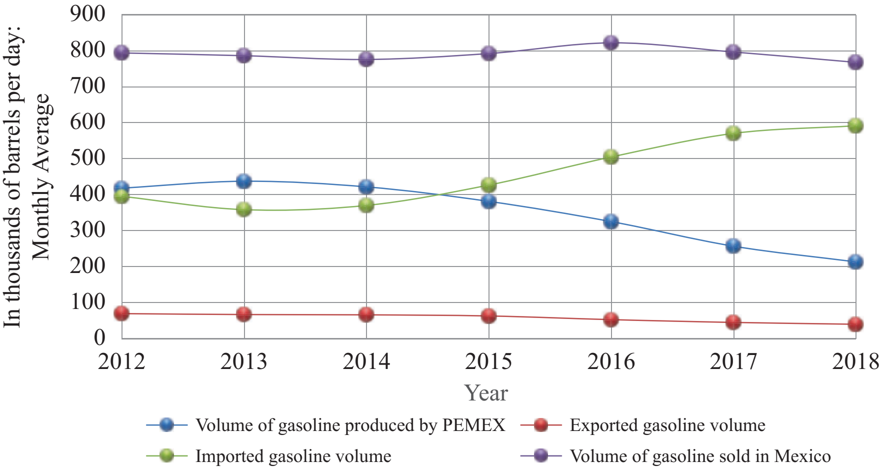


Fig. 10.15 Origin and consumption of gasoline in Mexico (data till October 2018). (SIE 2018a)

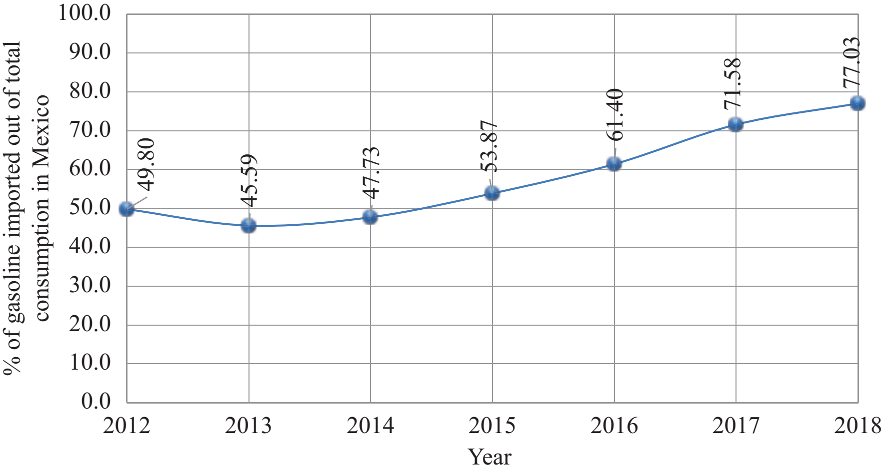


Fig. 10.16 Annual behavior of gasoline imports in Mexico (data till October 2018). (PEMEX 2018)

gasoline prices and exchange rate. Therefore, it must be emphasized that, to meet the domestic fuel demands, PEMEX is importing significant volumes of gasoline (Rodríguez 2017).

Gasoline is expensive in Mexico as compared to the prices in many of the other countries. The tax burden is also high in the Mexico. The international price of fuel type called “Magna” is 1.35 US$ gal^{-1}, whereas after the profit margins, taxes, fiscal

Table 10.1 Structure of gasoline prices in Mexico (December, 2016)

	Gasoline less than 92 octane (Magna) (US$ gal^{-1})[a]	Gasoline greater than or equal to 92 octane (Premium) (US$ gal^{-1})[a]
Reference price	1.35	1.45
Margin	0.34	0.49
Special tax on production and services (IEPS)	0.49	0.35
IEPS waw	0.78	0.66
Fiscal stimulus	-0.09	-0.11
Supplementary fee	-0.20	-0.19
Other charges	0.44	0.48
Maximum price	2.62	2.77

[a]Exchange rate as of December 2016, 1 USD$= 20.5 MEX Peso
SIE (2018b)

stimuli, supplementary rates, and other charges, its price rises up to 2.62 US$ gal^{-1} (SIE 2017), which represents an increase of 94%. Table 10.1 shows a comparison for the price structure of "Premium gasoline," which has an octane rating of 92 or more, against the prices for "Magna" having octane number less than 92. Currently, the retail price of gasoline in Mexico is liberalized and adjusted daily according to international prices.

Vehicles of diverse model years and brands are in circulation in Mexico (Figs. 10.17 and 10.18). Although a high percentage of cars (34%) are of recent years (2010 to 2015), for the rest, age is a limiting factor which would hinder the success of ethanol as a biofuel. The heterogeneity of vehicles would prevent vast majority of them from being able to use a blend of fuel ethanol with gasoline or biodiesel. It is therefore necessary to create a pilot program for these vehicles using different blending levels and then evaluate their performance and emission to establish an ethanol program considering cities, elevation, and ambient temperatures.

The use of bioethanol in internal combustion engines does not require major modifications as long as the proportion does not exceed 20% of ethanol in the blend. The addition of even 10% (v/v) bioethanol to the gasoline can increase the quality of the fuel as it contributes a greater amount of oxygen, increasing the efficiency of combustion, and reduces proportion of sulfur, aromatic compounds, and olefins (Cavalett et al. 2013). Currently, Methyl Tert-Butyl Ether (MTBE) is used in Mexico as a gasoline oxygenator. This additive was first used in unleaded gasoline to increase its octane rating in cities with a high population density such as Mexico City, Guadalajara, and Monterrey, keeping in view the atmosphere's increased carbon dioxide content in winters (Hernandez et al. 2014).

The implementation of bioethanol as a biofuel, either directly at 100% or as a gasoline additive, presents serious problems of acceptance in Mexico. The consumers are reluctant to espouse any new kind of fuel due to lack of information about the capacity of their cars to utilize the blended fuel. Moreover, sometimes, the

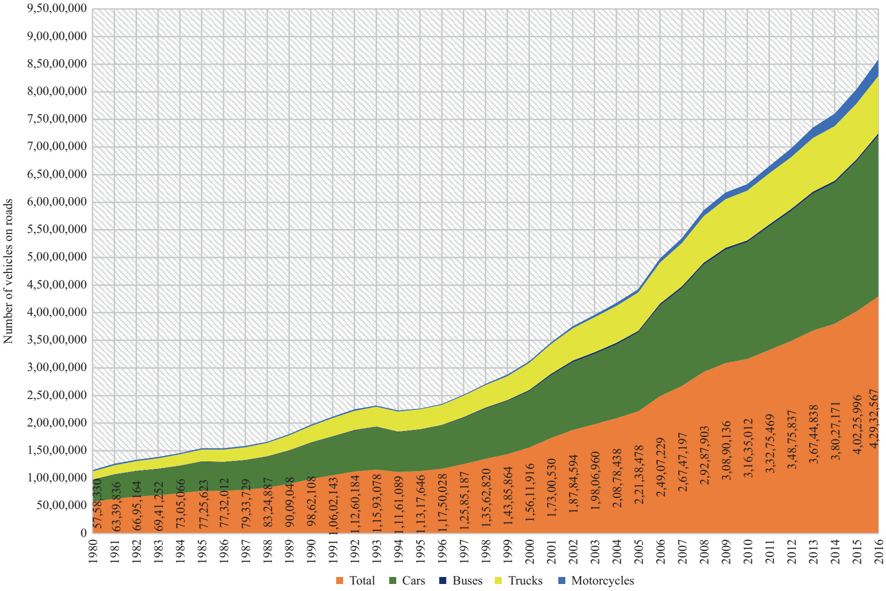


Fig. 10.17 Motor vehicles in circulation in Mexico. (National Institute of Statistics and Geography [INEGI] 2017)

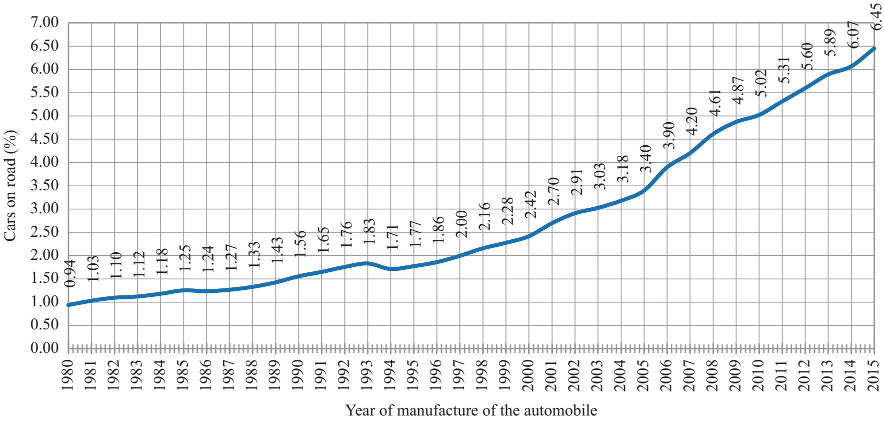


Fig. 10.18 Cars in circulation in Mexico classified by year of manufacture. (INEGI 2017)

entities that are responsible for producing or importing fuels also do not encourage bioethanol due to economic interests in the use of petroleum. However, the effectiveness of bioethanol is being demonstrated in many countries that are implementing measures and mandates to favor the use of this fuel not only for economic but mainly for environmental implications based on decision-making oriented toward the pursuit of sustainable development.

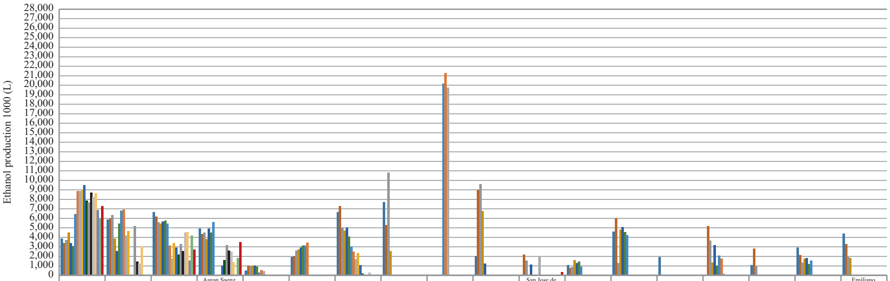
Castillo-Hernández et al. (2012) conducted the physicochemical characterization of commercial Mexican gasoline (PEMEX Magna and Premium) using 10% and 15% blends of anhydrous ethanol. They reported that the ethanol-gasoline blends had higher Octane Numbers as compared to the commercial gasoline, while conserving an appropriate Distillation Index at the same time. The Cetane Number showed a substantial decrease, whereas the Heating Value was negatively affected by the addition of ethanol. Nevertheless, taking into account the carbon credits for using a renewable fuel, reformulated conventional gasoline in Mexico would imply a maximum theoretical reduction of 7.5% in CO_2 emissions, whereas ethanol blends would represent a 9.2% decline.

The Mexican sugar industry has good potential for ethanol production (García et al. 2017). The country has harvested a surplus of sugarcane in recent years for a diversified production of food, feed, liquid and solid biofuels, and green chemicals, to some extent. However, no industrial-scale fermentation or distillation facilities have been available to turn sugarcane into biofuel. Furthermore, no serious efforts have been devoted to develop domestic biofuel market for the transportation sector (Nunez 2016). To take advantage from bioethanol blending, a comprehensive policy promoting the ethanol production and use in Mexico is required. The first step in this regard is to replace the use of oil-derived oxygenates that are imported by PEMEX and the second one is to blend ethanol with the gasoline to serve the purpose (Galicia-Medina et al. 2018; Garcia-Chavez 2015).

10.5 Current Status of Sugarcane Ethanol Production for Fuel Purposes

In Mexico, molasses is most abundantly available feedstock for ethanol production. Its production was 1.7 million tons (Mt) in 2016/2017 harvest season (CONADESUCA 2017). However, the environmental and socioeconomic sustainability of biofuel (ethanol) production for use as a potential additive for gasoline remains uncertain as this area of opportunity has been totally untapped among the socioeconomic and environmental goals by Mexican government, the sugar industry, and other stakeholders. This has already led to approximately 80% reduction in ethanol production in sugar mills having the capacity for converting sugars into ethanol, remaining at practically the same level throughout the last decade, as 97.2% of the main raw material, molasses, has been allocated for other uses or exports (Figs. 10.19, 10.20, 10.21, and 10.22).

In last decade, 17 of 64 sugar mills were producing ethanol (San Sebastian, Emiliano Zapata, San Cristobal, Calipam, La Joya, San José de Abajo, La Providencia, Independence, San Pedro, El Carmen, El Mante, Constancia, Aarón Sáenz Garza, San Nicolás, Tamazula, Pujiltic and La Gloria); by 2013, the number reduced to only 6 of 57 operating sugar mills (Pujiltic, San Nicolás, Tamazula, Aarón Sáenz Garza, Constancia and La Gloria), whereas four autonomous distilleries



	Pujiltic (La Fe)	San Nicolas	Tamazula	Aaron Saenz Garza	Calipam	El Carmen	Constancia	San Cristobal	La Gloria	Independencia	San Jose de Abajo	La Joya	El Mante	Los Mochis	San Pedro	El Potrero	La Providencia	Emiliano Zapata
1999	38,62,095	58,89,347	66,31,380	49,29,511	4,80,949	19,15,800	66,43,000	77,09,082		20,51,000		10,90,000	45,82,250	19,27,640		10,89,270	29,16,338	44,09,566
2000	34,10,968	59,74,729	61,94,600	43,62,575	10,41,174	20,08,000	72,69,000	52,69,538		89,58,934	21,83,000	7,59,700	60,33,000		51,79,904	28,10,873	21,18,147	32,65,577
2001	36,87,604	63,21,279	55,78,000	44,99,250	9,10,220	25,96,000	49,97,040	1,08,09,678		96,11,879	15,52,000	8,68,325	12,66,805		36,55,000	9,10,575	13,25,000	19,08,777
2002	44,83,954	38,52,460	54,20,000	38,30,300	10,38,471	26,88,600	46,86,300	25,77,645		67,54,702		15,95,588	48,05,085		13,51,000		17,52,360	18,24,727
2003	33,73,004	25,75,437	56,43,750	49,48,000	10,00,758	29,23,000	49,97,400			12,50,908	11,18,000	13,07,000	50,82,300		32,06,000		18,18,471	
2004	30,73,299	54,17,627	57,46,895	44,86,671	9,39,618	31,52,100	40,55,000					14,35,700	45,37,008		10,45,000		11,71,886	
2005	64,58,594	68,09,642	54,37,342	55,81,691	3,02,087	31,39,200	30,15,000		2,01,68,528			9,08,371	42,58,305		20,76,000		15,64,238	
2006	88,69,274	69,02,106	31,31,710		5,62,244	34,64,800	24,78,806		2,12,61,090			56,828			17,77,000			
2007	88,39,667	41,59,085	17,59,000		4,25,579		17,09,023		1,97,50,705		20,26,900				1,96,000			
2008	90,06,145	46,45,552	34,09,430				23,66,399											
2009	94,91,980		29,16,370	10,21,927			10,74,196											
2010	78,55,990		21,72,712	16,07,991			1,90,000											
2011	76,65,395	51,96,380	32,84,777	31,95,965														
2012	87,25,000	14,24,000	25,77,000	25,84,000														
2013	82,30,028	12,14,095	44,80,870	24,80,422			2,80,548											
2014	86,28,820	30,11,663	45,80,000	13,87,371														
2015	68,46,633		15,65,500															
2016	60,45,103		41,85,000	17,98,986														
2017	72,73,942		27,34,800	34,81,710					0		3,26,000		95,697					

Fig. 10.19 Ethanol production in sugar mills. (National Confederation of Rural Property Owners [CNPR] 2017 and CONADESUCA 2018)

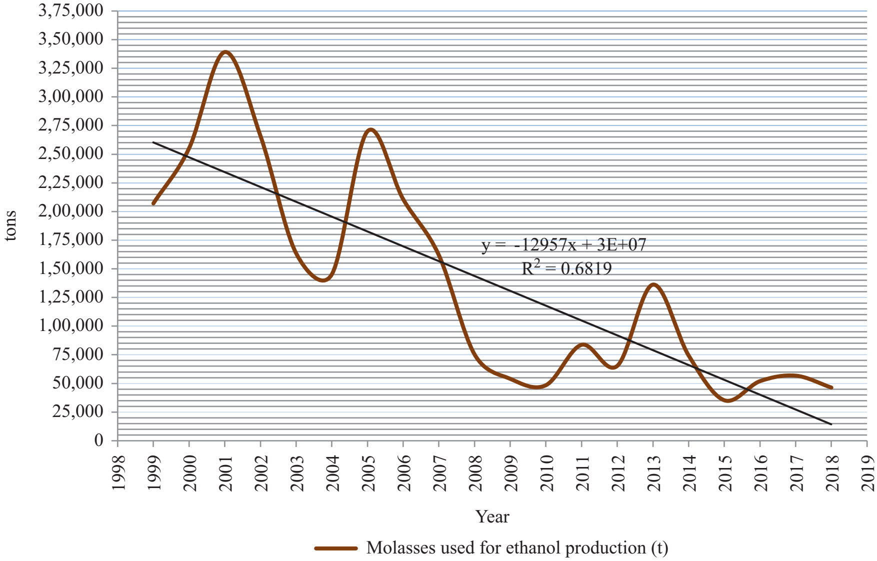


Fig. 10.20 Molasses (t) for ethanol production in sugar mills. (CNPR 2017; CONADESUCA 2017)

employing cane juice as feedstock for fermentation were operational in the same year. In 2016/2017, 13,816,452 L of ethanol was produced in 6 sugar mills (11.7%) out of the 51 mills in operation (Figs. 10.23, 10.24, and 10.25). The decline in ethanol production had a direct relationship with the prices of cane, sugar, raw material,

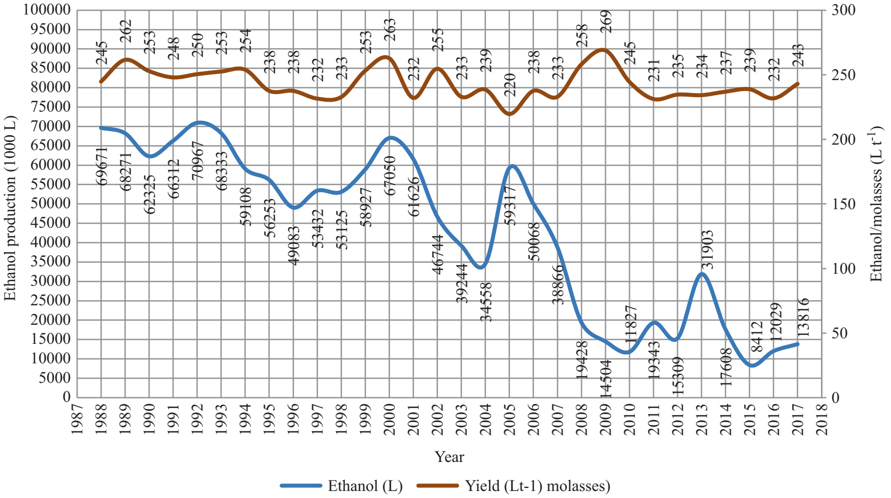


Fig. 10.21 Yield of ethanol from molasses in Mexico. (CNPR 2017; CONADESUCA 2017)

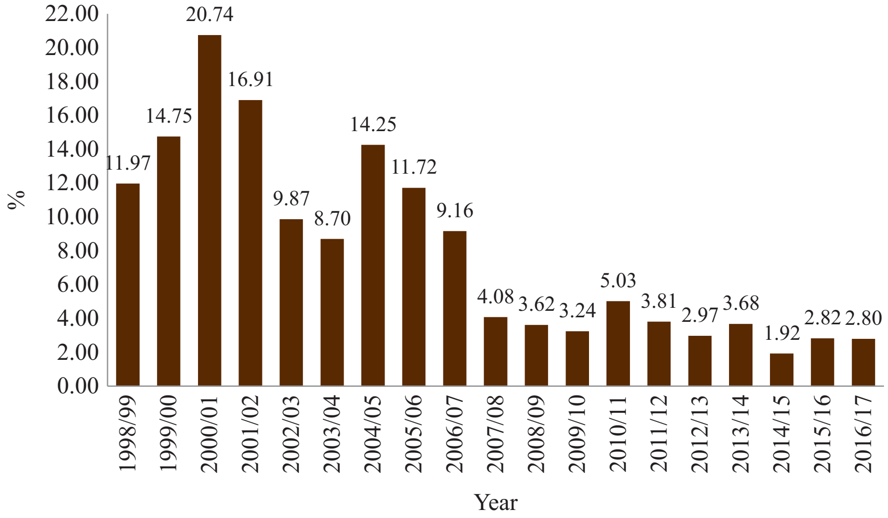


Fig. 10.22 Percentage of molasses used for the production of ethanol. (CNPR 2017; CONADESUCA 2017)

and the productivity (t ha^{-1}). With the passage of time, sugarcane yields have remained nearly constant, the harvested acreage has increased, whereas ethanol production has declined.

Ethanol production in Mexico is influenced by various factors (Fig. 10.26). While analyzing causal loops of ethanol production from sugarcane molasses and cane juice, it has been determined that the sugar/ethanol is dictated majorly by two

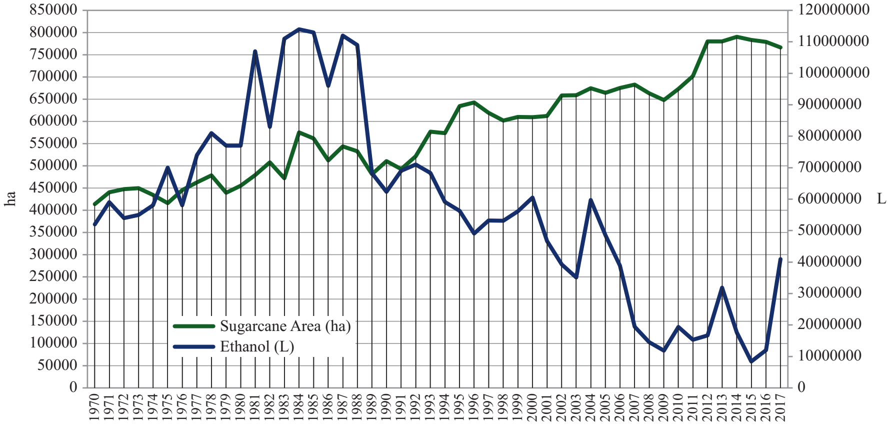


Fig. 10.23 Cane acreage and ethanol production (1970 to 2017). (CNPR 2017; CONADESUCA 2017)

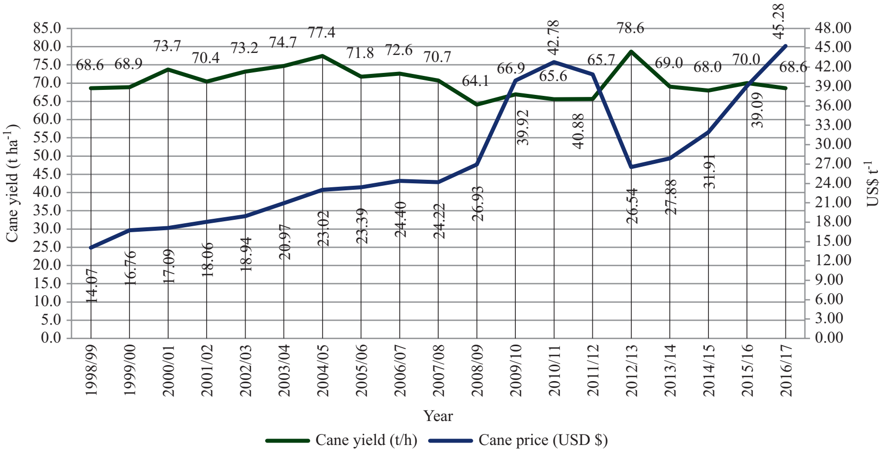


Fig. 10.24 Cane yield and price per ton over the years. (CNPR 2017; CONADESUCA 2017)

loops of balance. The relationship between molasses stock and bioethanol production is positive, while the relationship in the opposite direction is negative as higher the molasses stock is, the greater the production of bioethanol will be. Similarly, if bioethanol stocks increase, the sales of bioethanol would be higher, which would ultimately lead to reduction in the stocks. Moreover, if the demand for ethanol increases, sugar production may reduce and a certain amount of cane juice can be used for ethanol production while maintaining a fixed amount of sugar according to the market (R1).

The relationship between productivity, acreage, sugar production, and the declining ethanol production is due to several factors (Acosta 2011). Some of major elements are as follows:

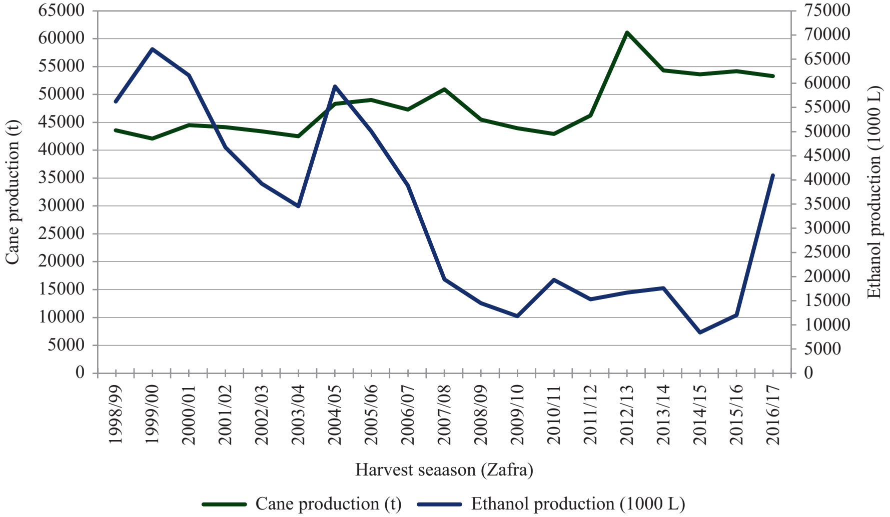


Fig. 10.25 Ethanol and sugarcane production over the years. (CNPR 2017; CONADESUCA 2017)

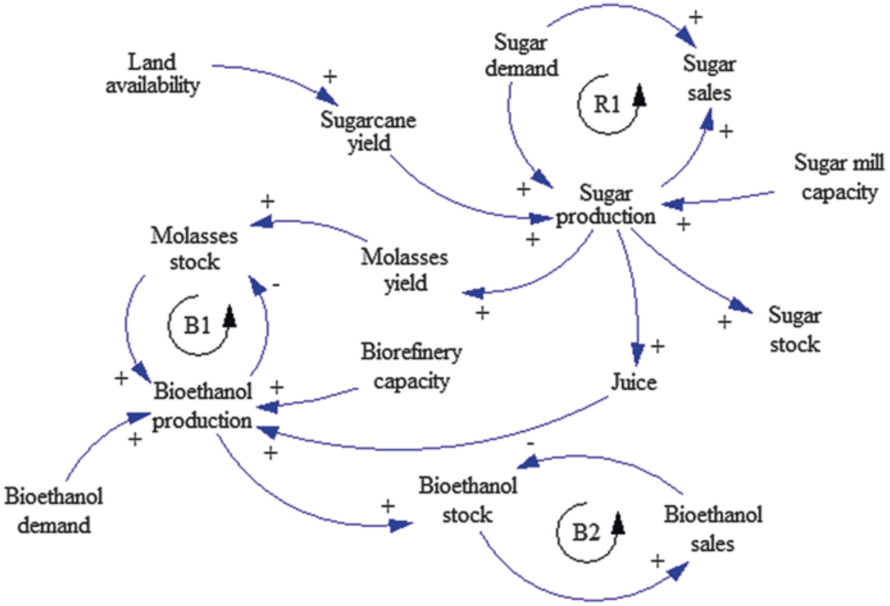


Fig. 10.26 Causal Loops Diagram for ethanol production from sugarcane juice and molasses. (Modified from Rendon-Sagardi et al. 2014)

1. Limited domestic ethanol demand as biofuel
2. High production costs of sugarcane as feedstock
3. Increased acreage, but low productivity and quality of raw material
4. Volatility in prices of molasses at domestic and export markets
5. Sugarcane price exclusively connected to the price of raw sugar
6. Higher income from molasses through other applications such as livestock feed or even exportation
7. Institutional limitations, absence of subsidies, and lack of infrastructure
8. Absence of environmental commitments

10.6 Electricity Cogeneration

Cogeneration of electricity, as part of an essential coproduction system along with sugar and ethanol, has been known for decades in Mexico. Yet, cogeneration technology is not matured and considered less efficient. Electric power generation, transformation, and distribution, as a public service, is responsibility of the Mexican state managed by The Federal Electricity Commission (CFE for its initials in Spanish) and the Mexican Energy Policy and Regulatory Framework. The sugar industry reaches an estimated potential of almost 1000 MW which can further be increased even more (Pérez-Denicia et al. 2017; Rincón et al. 2014) (Fig. 10.27).

Cogeneration can additionally enhance the profitability of mills if they make use of bagasse and sugarcane trash for this purpose. The efficiency of the cogeneration can be increased by replacing the traditional boilers with high pressure boilers. In

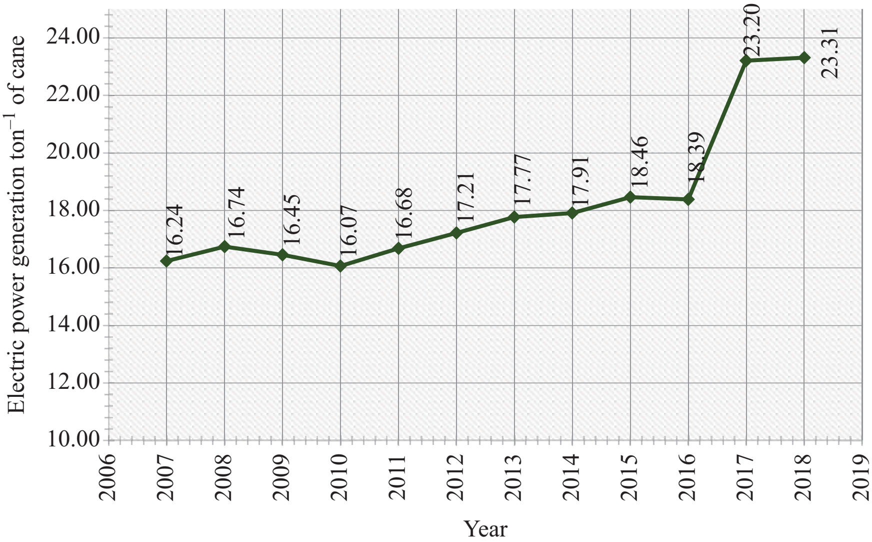


Fig. 10.27 Electric power generation ton^{-1} of cane. (CONADESUCA 2017)

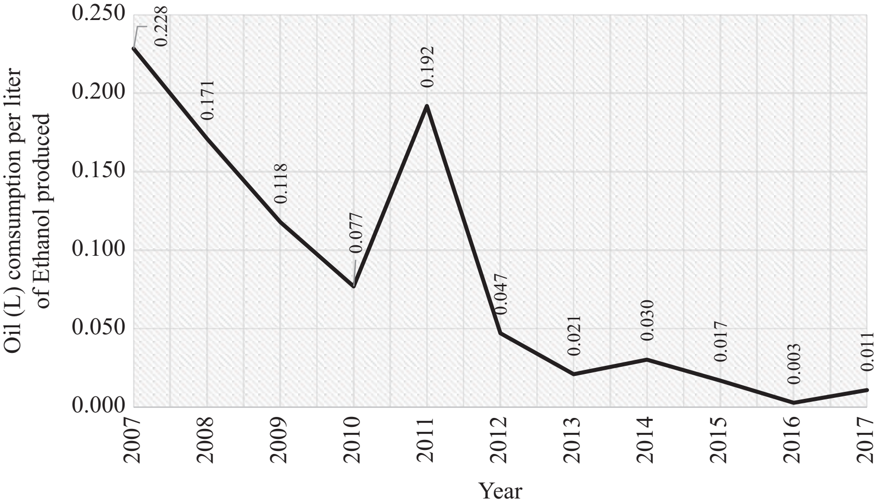


Fig. 10.28 Oil consumption per liter of ethanol produced in sugar mills. (CONADESUCA 2017)

most cases, low efficiency boilers and steam turbines are still employing oil as fuel. Additionally, at most of the units, energy production from bagasse is inefficient. Consequently, production units are not able to fully cover their own energy requirements. However, situation is improving over time, and the use of oil in ethanol production has declined in recent years (Fig. 10.28).

Mexican sugar mills focus only on the extraction of energy contained in the sugarcane juice, thus wasting the energy contained in the bagasse and straw (sugarcane crop residues, meaning tops, leaves, and straw). By only making use of the juice, one third of the energy contained in sugarcane is extracted efficiently. The remaining one third energy in sugarcane present in bagasse is heavily underutilized because of the low energy efficiency of the cogeneration systems. Straw, which forms another one third portion of energy contained in sugarcane, is not being used for this purpose at all, as it is burnt in the field before harvesting (Bustamante and Cerutti 2016).

According to the Mexican Ministry of Energy (SENER), in 2014, Mexico produced 8,826 PetaJoule of energy from the following sources: fossil fuels 91.31% (crude oil 63.42%, natural gas 23.56%, coal 3.44%, and condensates from natural gas production 0.89%), nuclear energy 1.14%, and renewables 7.56% (hydroelectric 1.59%, geothermal 1.47%, solar 0.10%, wind 0.26%, biomass 4.12%, and biogas 0.02%). These statistics indicate that fossil fuels dominate the Mexican energy matrix, and that biomass represents only a small proportion of the total (Alemán-Nava et al. 2015).

10.7 Major Uncertainties of Cane Energy Production in Mexico

Cane biofuels, when adopted, need to be kept under regulatory checks. Sugarcane expansion cannot be done in an unwise manner. García et al. (2017) reported that first-generation ethanol in Mexico can pose negative environmental impacts too such as increase in CO_2 emissions due to land use change from grasslands, jungles, and other forest crops; loss of biodiversity due to higher deforestation; and threats to food safety if the crop competes for the soil used for food growing soils, which can also cause soil erosion as well as depletion of water resources. Moreover, regarding ethanol engenderment in Mexico, water use is the most sensitive indicator of sustainability; hence, sustainable production of sugarcane can only be conducted in regions where there is an abundance of rainwater and suitable soils.

It can be estimated that Mexico is not expected to meet ambitious biofuel targets in the short term because of:

- Huge reserves of oil and natural gas in Mexico
- Poor economic and growth opportunities in traditional agribusiness
- Low level of investment in research, innovation, and development of domestic technologies for ethanol (1G, and 2G)
- Effects of unfavorable weather, El Nino, and La Nina (ENSO) on rainfed agriculture
- Low scale of production as 90% of Mexican sugarcane growers have small farms
- Low ethanol yield and production efficiencies
- Unavailability of optimized fermentation and pretreatment approaches
- High infrastructure costs for improvements in existing milling procedures
- Lack of interest and knowledge of drivers regarding ethanol-based fuels
- The food versus fuel issue if sugarcane is expanded over lands used for food production currently
- Absence of a prioritized national policy

Because of these uncertainties and challenges, bioethanol is currently produced only in some of the sugar mills which have infrastructure for distillation; however, most of the ethanol is employed for alcoholic beverages and for applications as a solvent in other industrial processes. Moreover, apart from sugar mills, units only involved in ethanol production are also operational in the country; nevertheless, ethanol yielded from them also meets the similar fates. It is clear that national ethanol policy is a multidimensional prerequisite for development of ethanol-based fuels in Mexico.

10.8 Possibilities of Crop Expansion: Agroecological Zoning (AEZ)

Agroecological Zoning (AEZ) is a plan to expand and technologically improve production of a crop in a particular region. AEZ is used as a tool to improve crop yields based on the analysis of climatic and edaphic information of the site, keeping in view the environmental conditions of soil and climate needs of the crop of interest. The main objective of AEZ is the identification of areas with agricultural potential for the given crop, using the spatial and simultaneous overlapping of information related to variables of interest about the environmental conditions. Geographic Information Systems (GIS) are used to identify the environmental limitations and, based on this, to estimate the optimum areas for crop cultivation evaluating climate, soil, and environmental variables. The AEZ and novel techniques such as maximum entropy modeling (MaxEnt), the Soil and Water Assessment Tool (SWAT), remote sensing, GIS and precision agriculture, and life cycle assessment (LCA) may contribute to achieving sustainability goals and supporting major strategic decisions to improve sugarcane crop yields and ethanol production (Aguilar-Rivera et al. 2010).

Valdez-Vazquez et al. (2010) concluded that Mexico is the third largest country in Latin America in terms of cropland area, and thus, it could become a central focus of attention for producing biofuels from biomass and crop residues in the future. Identification of potential municipalities or agroecological zones where the biomass (sugars and fiber) production would be high is important since it constitutes the first step toward evaluating the land suitability and helps in accurately estimating the possible crop and bioenergy production capacity from such areas. Sugarcane cultivation is integrated and optimized into an established production system in Jalisco, Michoacán, Puebla, and Morelos, which allows competitive yields from very small farms, even if optimal environmental conditions are not available. In rest of the country, the potential yield can only be reached if optimal environmental conditions are identified based on edaphic and environmental requirements.

We used agroecological zoning to construct a distribution modeling for the sugarcane crop using Maximum Entropy Species Distribution Modeling (MAXENT®), which produces a continuous binomial probability distribution representing habitat suitability according to the climate variables (Phillips et al. 2006, 2017). Firstly, a cane polygon was developed using ILWIS 3.1 software (Integrated Land and Water Information System) and GIS tools ESRI ArcGIS 10.1 (Fig. 10.29). Secondly, the soil and climate conditions prevalent for modelling, and various climate variables including one topographical variable with a resolution of 30 arcseconds or around 1 km^2, were applied. Finally, we used nine layers related to the Mexican soil properties at a scale of 1:1000000 (Cruz-Cárdenas et al. 2014; Merow et al. 2013) (Tables 10.2, 10.3 and Fig. 10.30).

From the analysis, it was determined that current sugarcane regions, Jalisco, Veracruz, and Sinaloa, have the largest acreage available with exceptional suitability for growing sugarcane and harvesting maximum yields. However, the states of Morelos, Sinaloa, and Nayarit have the greatest potential in terms of land suitable

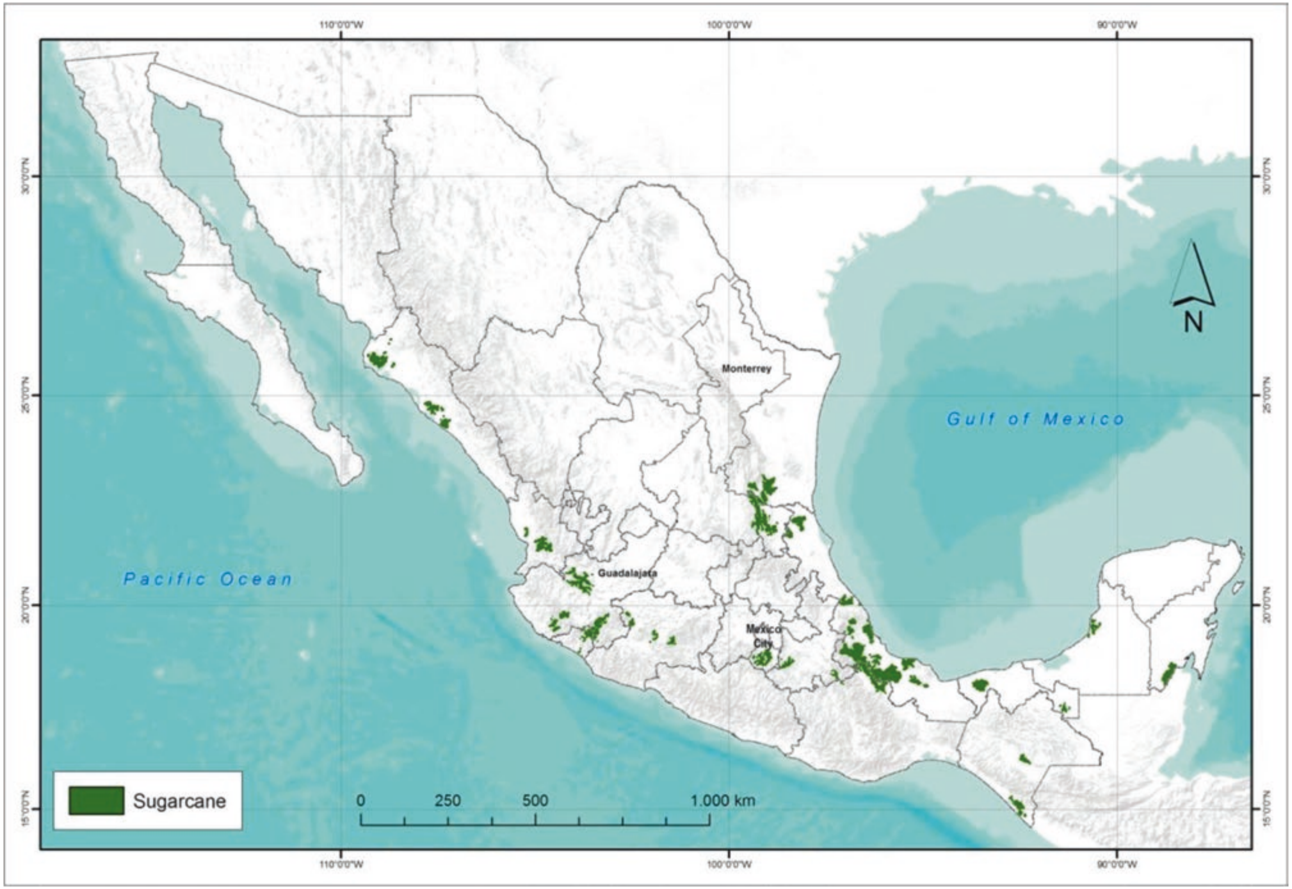


Fig. 10.29 Sugarcane supply zones in Mexico and Mexico City, Guadalajara, and Monterrey. (Aguilar-Rivera et al. 2017)

Table 10.2 Agroecological suitability (ha) for sugarcane crop fields in Mexico

State	Very low	Low	Medium	High	Total
Morelos	569.84	852.31	447.06	3001.98	4871.19
Sinaloa	7933.96	3747.02	12101.31	31646.99	55429.29
Nayarit	2368.99	1756.13	8050.81	15516.19	27692.12
Colima	36.46	1748.17	1087.43	2711.49	5583.54
Jalisco	33597.62	3217.22	4712.41	36803.38	78330.64
Veracruz	10100.01	18922.96	10055.41	31805.88	70884.26
Campeche	1875.99	29314.32	9284.74	15587.25	56062.30
Chiapas	20573.54	26697.86	12398.70	13499.60	73169.70
San Luis Potosí	36245.23	5499.94	8486.97	10616.60	60848.73
Oaxaca	35404.91	27805.21	15244.40	15215.62	93670.14
Michoacán	33429.20	12544.30	4049.53	8445.33	58468.37
Tamaulipas	45759.95	11387.55	9653.53	11102.85	77903.87
Tabasco	2981.19	7910.69	10382.15	3236.60	24510.62
Puebla	17970.94	4341.55	8295.73	3611.52	34219.75
Quintana Roo	22437.39	19666.90	0	0	42104.29
National	271285.22	175412.13	114250.16	202801.28	763748.80

Table 10.3 Agroecological suitability (% of land) for sugarcane crop fields in Mexico

State	Very low	Low	Medium	High
Morelos	11.70	17.50	9.18	61.63
Sinaloa	14.31	6.76	21.83	57.09
Nayarit	8.55	6.34	29.07	56.03
Colima	0.65	31.31	19.48	48.56
Jalisco	42.89	4.11	6.02	46.98
Veracruz	14.25	26.70	14.19	44.87
Campeche	3.35	52.29	16.56	27.80
Chiapas	28.12	36.49	16.95	18.45
San Luis Potosí	59.57	9.04	13.95	17.45
Oaxaca	37.80	29.68	16.27	16.24
Michoacán	57.17	21.45	6.93	14.44
Tamaulipas	58.74	14.62	12.39	14.25
Tabasco	12.16	32.27	42.36	13.20
Puebla	52.52	12.69	24.24	10.55
Quintana Roo	53.29	46.71	0.00	0.00
National	30.34	23.20	16.63	29.84

for the cultivation of sugarcane in relation to current acreage (ha). At the national level, less than a third of the agricultural land presented a high level of suitability for cultivation of sugarcane (29.84%).

Mexico produces sugar with lower environmental impact than other countries because it has a good agroclimatic suitability for the crop. Therefore, if properly planned, the production of sugarcane, sugar, and ethanol could be carried out with less water and fertilizer use and fewer emissions. Crop production in the regions

Fig. 10.30 Agroecological suitability in Mexican sugarcane regions. (Aguilar-Rivera et al. 2019)

identified through AEZ analysis can help enhance sugarcane cropping in Mexico. According to Garcia-Chavez (2015), the production of anhydrous and hydrated ethanol in Mexico is economically viable and has domestic and international market potential; however, it requires concrete efforts by stakeholders to stimulate investments in sugarcane fields and sugar mills to increase productivity, diversify the uses of sugarcane, and increase its sustainability and competitiveness.

10.9 Enhancing the Sugarcane Biofuel Production in Mexico

Keeping in view the current status of biofuels in Mexico, it is necessary to reshape the sugar industry for enhancing ethanol production considering the 2030 Agenda for Sustainable Development, goals of BONSUCRO, FSSC 22000 Food Safety System Certification, and other frameworks. One of the major factors is the incorporation of scientific research, technological developments, and innovations carried out by Mexican researchers in industry and crop production (Gracida Rodríguez and Pérez-Díaz 2014; Ramos-Hernández et al. 2016), which can help in modernizing the value chain involving sugarcane agronomy, transport, distillation, and marketing system.

Rendon-Sagardi et al. (2014) mentioned that Mexico is a country with fuel ethanol production capacities, but no policy programs to support the same. Thus, the cane millers in the region follow an opportunistic strategy: the syrup is crystallized into the maximum amounts of sugar for domestic consumption and exports, and most of the remainder is exported as feedstock molasses, decreasing its use as raw material for ethanol production. Even though this means that their investment in fuel ethanol production capacity remains underutilized, the strategy still provides the best returns in an environment characterized by fairly weak biofuel legislation (Castañeda-Ayarza and Cortez 2017).

Regarding crop production, it is necessary to move toward precision agriculture (PA) for yield prediction and growth monitoring for enhancing the sustainable cultivation of sugarcane under rainfed and irrigated conditions. Moreover, modernization of sugarcane fields based on agroecological zoning will also help. An emphasis on crop grower throughout the value chain should also be placed. Further, a differential pricing mechanism should be established based on the final use of the crop for ethanol, or sugar production. For crop improvement, transgenic sugarcane can also reduce the costs involved in sugarcane cropping, making it far more profitable.

At the milling levels, there is need to enhance ethanol engenderment efficiency. Also, second-generation ethanol production should be adopted apart from installation of novel pretreatment options which would make the process more profitable and feasible. Additionally, employing cane-generated electric power in milling operations will decrease the fossil fuel consumption. Economic incentives are also necessary to help the construction and modernization of milling and distillation operations. Furthermore, it is necessary to implement biotechnological approaches in the fermentation process, which could revolutionize the cost-benefit ratio of this phenomenon once established.

10.10 Prospects of Cane Bioenergy in Mexico

Elizondo and Boyd (2017) proposed that policymakers made the decision to foster the use of ethanol because of its potential environmental advantages along with its possible benefits to energy security and rural development. According to Alemán-Nava et al. (2015) and Rios and Kaltschmitt (2013), Mexico's energy needs are expected to increase due to population growth in the years to come. Thus, if adopted, the overall potential of biomass for energy production in Mexico will account for only 39% and 31% on average of the final energy demand in Mexico for the years 2020 and 2030, respectively. Therefore, it is likely that in the future bioenergy will play a role, but with decreasing importance in Mexican energy system because of the potential effects of the Mexican energy sector's reformation targeting possible exploitation of new oil and natural gas deposits (Elizondo et al. 2017). On the other hand, the land available for energy crop production and the provision of forestry wood residues are expected to decline; it is therefore essential to develop strategies and scenarios for increased use of different biomass sources and improve the technical aspects of first- as well as second-generation ethanol production.

Mexican government and the Energy Regulatory Commission recently published and approved Mexican official standard "NOM-016-CRE-2016," which allows the mixing and sale of up to 5.8% (v/v) blend of ethanol anhydrous oxygenate in regular and premium gasoline sold by PEMEX. The official standard does not, however, include the three major metropolitan areas: Mexico City, Guadalajara, and Monterrey. Moreover, there are still several technological barriers that limit the full potential of this approach and that are the topics of active research by Mexican researchers (Chavez-Baeza and Sheinbaum-Pardo 2014).

In spite of all the hurdles, keeping in view current production capacity and distilling technologies available, only sugarcane industry can generate enough supplies to target ethanol blending in Mexico. If new energy supplies and biofuels such as ethanol or biodiesel are not incorporated, prioritizing the renewable fuels to diversify the energy sources in the Mexican energy market, the country may face a fuel shortage in future. Rendon-Sagardi et al. (2014) commented that based on international experiences, the use of ethanol to produce biofuel in Mexico represents the beginning of a transition process leading to sustainable transportation systems.

10.11 Conclusion

Mexico has good agroclimatic conditions for growing and thriving sugarcane crop. However, currently, use of sugarcane ethanol as a biofuel in Mexico is hindered by many factors, which mainly include Mexico's own oil reserves limiting the need to move toward novel options, absence of a multidimensional national policy for biofuel adoption, unavailability of efficient technologies in sugar mills and distilleries, and use of ethanol in other industries. In the future, cane ethanol can gain importance in Mexico for environmental and climatic benefits rather than financial ones. In such a scenario, investments in the sector for increasing production efficiency and crop yields will play a critical role. Moreover, a national policy will indeed be required for launching a multidimensional approach to make the ethanol blending market competitive. Since sugarcane, as a crop, has good prospects in Mexico, the biorefinery concept at the sugar mills for producing first- and second-generation ethanol along with sugar production can benefit the stakeholders involved in sugarcane milling and cropping, apart from meeting the climate change commitments. Commencing from lower blending levels will be a good start as it won't demand major investments or changes in the vehicles.

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Chapter 11
Sugarcane Biofuel Production in Colombia

Kelly Johana Dussán, Giuliano Formaggio de Mello, Bruna Gava Floriam, Mariana Ortiz Sanchez, Estefanny Carmona Garcia, Carlos Ariel Cardona, and Débora Danielle Virginio Silva

11.1 Introduction

There is a worldwide consensus to find renewable energy sources to replace fossil fuel-based energy sources. Colombia, as many other countries, has been looking for alternatives to broaden its energy matrix, reduce its dependence on fossil fuels, and address its environmental concerns.

Added to the high prices of petroleum-based fuels, the use of such fuels is also related to the high emission of greenhouse gases (GHG). With the aim of reducing environmental problems caused by increased GHG emissions, governments have invested in the research and development (R&D) of renewable energy, mainly from biomass (Ottinger 2009). The use of biofuels, renewable energy sources, shows the advantage of producing clean energy and helps to boost the economy in developing countries providing jobs without needing to import equipment or expertise, using local feedstock. (Haubensak and Rutherford 2011; Ottinger 2009).

According to Cortés-Marín and Ciro-Velázquez (2011), unlike the oil industry, the new agro-industry involves a productive chain that is correlated to different economic sectors, especially in jobs and the development of agriculture and agribusiness. For bioenergy engenderment, sugarcane stands out due to its high photosynthetic and biomass production capacities and extraordinary carbohydrate contents, which can be transformed into biofuels (Cordovés Herrera 1999; Hoang et al. 2015). Sugarcane biomass can be used integrally for producing first-generation (1G) ethanol from juice extraction; electricity and high-pressure steam by burning

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bagasse and straw; and second-generation (2G) ethanol from bagasse and straw. In addition, all these productive processes can be coupled to the processes for the production of biodiesel and other biobased chemicals in biorefineries, increasing economic and environmental advantages (Choi et al. 2015; Daza Serna et al. 2016).

Considering this, in the sections below, this chapter focuses on some advantages and bottlenecks that bioenergy production from sugarcane in Colombia presents.

11.2 Status of the Sugarcane Crop in the Country

Colombia is the world's seventh greatest producer of sugarcane in terms of milled weight (Bezerra and Ragauskas 2016) with a production of more than 23 million metric tons per year (ASOCAÑA 2017), which corresponds to about 1.5% of the global production (Bezerra and Ragauskas 2016). The country also occupies the position of the second greatest producer in Latin America, with this production distributed in a planting area of approximately 238,000 ha. Around 75% of this land belongs to more than 2750 sugarcane providers, while the rest is the property of 14 sugarcane mills. This means that Colombia's sugarcane agriculture is mostly based on small properties, of which the size of the vast majority is smaller than 60 ha (ASOCAÑA 2017).

In most countries, sugarcane is a product that can be harvested, on average, 4–6 months a year (Verheye 2010). However, Colombia is privileged to have one of the world's best agro-climatic conditions for sugarcane production (Londoño 2016). The excellent combination of humidity, sunlight, temperature, and altitude in the valley of the Cauca River, the main Colombian sugarcane-producing area, provides the optimum conditions for full-year harvests. This leads to double sugarcane yields per unit of land and lower fixed unit costs per unit output (estimated to be half or even a third of those found in other countries) (Verheye 2010). Thus, the valley of the Cauca River is considered one of the most important agro-industrial clusters in the country (Londoño 2016). These characteristics place the Colombian sugar industry as the global leader in productivity per unit area, as shown in Fig. 11.1. In addition, the proximity to the port of Buenaventura contributes to the competitiveness of the sector by lowering the transportation costs for sugar exporting (Verheye 2010).

In Colombia, approximately 99% of the total production is located in the west zones close to the Cauca River (Moncada et al. 2013) in a region known as the Cauca River Valley, which extends over five departments: Cauca, Valle del Cauca, Quindío, Risaralda, and Caldas (Vargas et al. 2017). The Cauca River Valley, having an approximate area of 448,000 ha (Delgadillo-Vargas et al. 2016), is characterized by intensive agriculture and high industrialization in projects related to sucrose, energy, sugar, and bioethanol (Vargas et al. 2017; Villamizar and Brown 2016). The sugarcane crop covers about 50% of the arable land of this region (Villamizar and Brown 2016). Moreover, 13 out of the 14 Colombian sugarcane mills are located

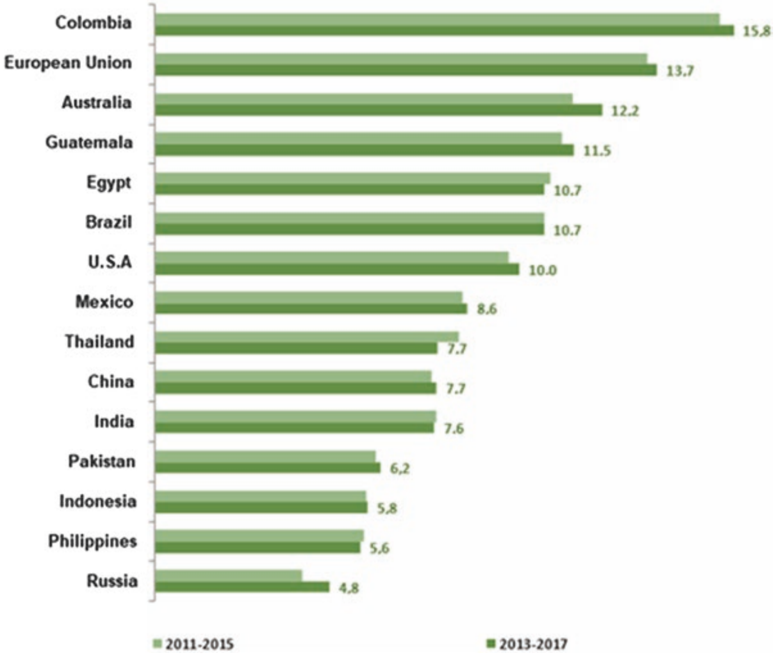

Fig. 11.1 Global sugar productivity indicator—main producing countries (tons of sugar per hectare). (Source: ASOCAÑA 2017)

in this territory, and its production has the potential of producing around 954,000 L/day of ethanol from sugarcane juice. This would represent the second largest ethanol producer in Latin America (Bezerra and Ragauskas 2016).

In geological terms, this valley is represented by a graben-type structure and is limited in its two flanks by regional faults that cross through the piedmont areas of the central and western Andean mountain chains (Delgadillo-Vargas et al. 2016). Figure 11.2 highlights the valley of the Cauca River territory, as well as its sugarcane mill distribution.

Although the valley of the Cauca River has the perfect conditions for sugarcane cultivation, the region is almost at full capacity with little land for expansion, and increases in productivity are the outcome of technology improvements and better weather (Gilbert and Huerta 2016). The Colombian Sugar Industry Research Center (Cenicaña), a private nonprofit company funded by donations from sugarcane mills, develops programs in order to improve the sector, in particularly applying new seed varieties that are better adapted to climate change and weather volatility (Cenicaña 2017a). Currently, more than 90% of the sugarcane-planted areas correspond to varieties developed by Cenicaña associated with the biological control of sugarcane pests (ASOCAÑA 2017).

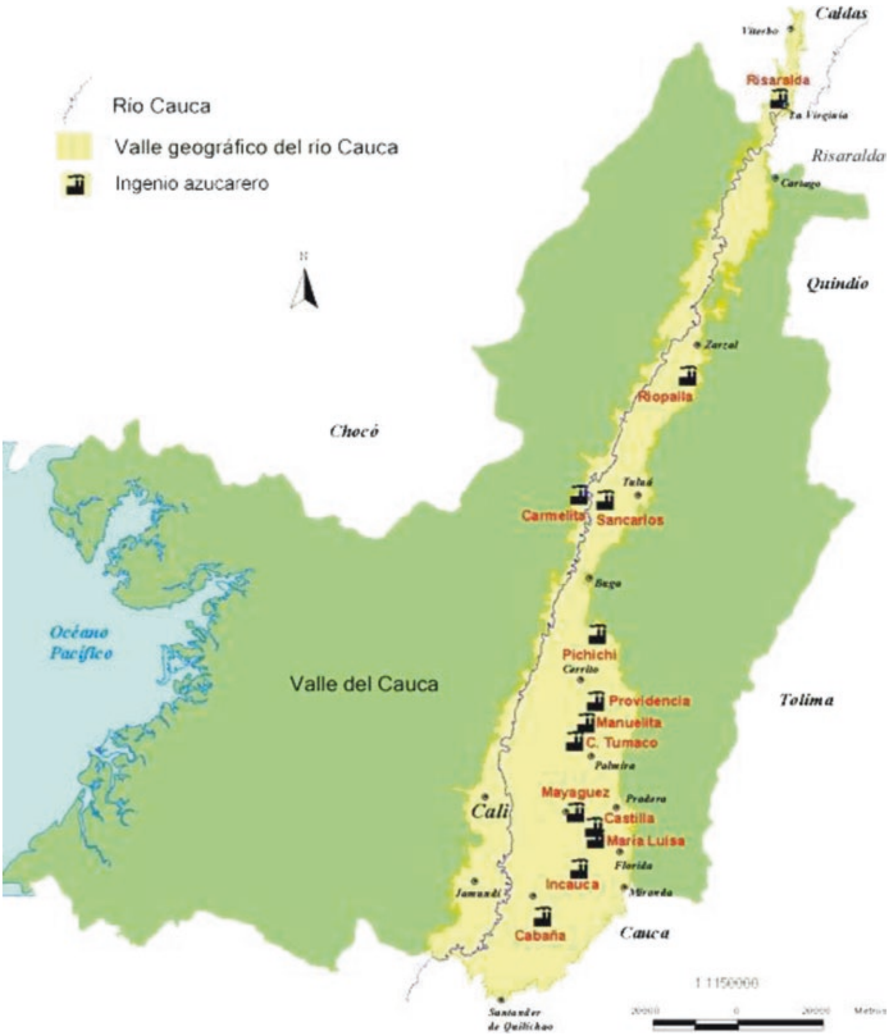

Fig. 11.2 Valley of the Cauca River region and locations of its sugarcane mills. (Source: Cenicaña 2017b)

11.3 The Sugar Industry of the Country

In this section, a study of the sugar industry in Colombia is developed, emphasizing the description of the sugarcane supply chain in Colombia. The evolution of the industry over the years, in turn, shows how the sugarcane industry has evolved under the concept of biorefineries and how this concept has affected the cane industry with the introduction of sugarcane biofuels. Finally, the potential growth of this industry in the country is also described.

Sugarcane (*Saccharum officinarum* L.) requires a wet and hot tropical climate alternating with dry periods and a great amount of light for optimal growth. For this reason, it is cultivated in tropical and subtropical zones. Sucrose is obtained from the juice that is extracted from the stem of the sugarcane plant. Sugar is considered as one of the most important basic products in the world market (Sánchez and Cardona 2007). The world production of sugar during the period 2009/2010 was 153.4 million metric tons, whereas by 2012/2013, the increase in 24.44 million metric tons was recorded resulting in a total of 177.84 million metric tons of sugar production. For the 2016/2017 period, the world production of sugar is estimated to be 170.81 million metric tons, which represents a decrease of approximately seven million metric tons in the world market, but following the predictions realized by the Statistics Portal, the world production of more than nine million metric tons of sugar is expected for the period of 2017/2018 (STATISTA 2017).

Colombia is considered as one of the largest producers of sugar in the world due to its extremely suitable agro-climatic conditions for sugarcane production. Another factor which contributes toward higher cane production per unit area in the country is the exemplary research and development support by the industry amounting approximately to $40 billion annually (Vega 2017). Colombia represents an example of optimal tropical conditions for the development of this industrial sector. In the country, sugar mills are affiliated to the agro-industrial association of sugarcane (ASOCAÑA), and Table 11.1 shows information about some of these sugar mills. Table 11.1 shows the variety of products that these facilities have to produce sugar, pure alcohol, energy, and compost, among others. These products are obtained after the integral processing of the feedstock, applying the emerging concept of biorefineries.

11.4 Sugarcane Supply Chain in Colombia

The sugar sector is mainly made up of two components: the first one is the sugarcane producers and the second one the sugarcane processors, i.e., sugarcane mills. These two components make up a conglomerate or sugar cluster (Sánchez and Cardona 2007). According to the agro-industrial association of sugarcane (ASOCAÑA) in Colombia, there are 225 thousand hectares of cane planted for sugar, of which 25% correspond to the lands owned by sugar mills and the remaining 75% to <2750 cane growers. These growers supply cane to 13 sugar mills in the regions: La Cabaña, Carmelita, Manuelita, María Luisa, Mayagüez, Pichichí, Risaralda, Sancarlos, Riopaila-Castilla, Incauca, Providencia, Central Sicarare, and Central Tumaco (ASOCAÑA 2016b). The first link in the supply chain is made up of producers of which 78% have a university education with vast experience in sugarcane cultivation, achieving yields of up to 13.46 tons of sugar per hectare harvested (Sánchez and Cardona 2007).

The Colombian sugar sector is a large agro-industrial cluster, unique in the geography and national economy, located in four departments (Cauca, Valle del Cauca,

Table 11.1 Sugar mills in Colombia

Sugar mill	Year of opening	Location	Products	Production
La Cabaña	1956	Cauca	Refined sugar White sugar Honey Energy cogeneration	Refined sugar: 400 tons/day
Carmelita	1965	Valle del Cauca	Refined sugar White sugar Honey Bagasse Cachaza	NR
Manuelita	1864	Palmira, Valle del Cauca	Sugar and sweetener Industrial sugar Biodiesel Bioethanol Stillage Bagasse Molasses Pure alcohol	Sugar, 2.600 tons/day Bioethanol, 250,000 liters/semester
Maria Luisa	1930	Valle del Cauca	Sugar	Nominal grinding of 750 tons of cane per day
Mayaguez	1937	Valle del Cauca	Sugar Fuel alcohol Energy cogeneration Compost	Nominal grinding of 2,450,000 tons of cane per year
Pichichi	1941	Valle del Cauca	Sugar	

Quindío, and Risaralda). The sugar cluster includes 13 sugar mills, 12 energy cogenerators, 6 distilleries of alcohol fuel, more than 2750 cane suppliers, 1 paper producer (Propal), 1 sucro-chemical company (Sucroal), more than 40 food companies, 3 soft drink companies, 8 wine and liquor companies, and more than 50 specialized suppliers (Londoño Capurro 2017).

The national consumption of sugar in Colombia in 2017 was 1.67 million tons, of which 65% corresponded to direct consumption in households and 35% to the manufacturing of food products and beverages for human consumption. In 2017, 703 thousand tons of sugar were exported mainly to the United States, Haiti, Spain, Peru, Ecuador, and Chile (ASOCAÑA 2018). In general, the sugar mills contribute significantly to the country's economy, not only directly but also because of the effects which their operations generate on other sectors—through large multiplier effects in the economy. The most important effects are on jobs, intermediate production, tax payments, the gross domestic product (PIB—annual growth rate), and salaries (ASOCAÑA 2016b).

Fedesarrollo (Fundación para la Educación Superior y el Desarrollo) presented the results of a study on the socioeconomic impacts of the Colombian sugar sector.

The main conclusions of the study indicate that for every job generated by the sugar mills, 28.4 additional jobs are generated in other sectors of the economy. Due to the manufacturing activity of the sugars mills, 265,000 jobs are generated throughout the whole value chain (Arbeláez et al. 2010).

In Colombia, the quality of life is better and the unsatisfied population is lower, regardless of the fact that public investment is low, in areas where sugarcane is cultivated, as compared to regions where other agricultural or agro-industrial activities are carried out. A better quality of life is reflected from higher schooling and literacy rate and the lower mortality rate of such departments. Likewise, the departments where cane is cultivated and destined to the sugar mills have less poverty than other departments having other crop cultivations. The unsatisfied basic needs of the population in the sugarcane department are below the national average (Arbeláez et al. 2010). Finally, the presence of the sugar mills makes the sugarcane department an area of influence, which has higher income, and more prosperous.

11.5 Evolution of the Sugarcane Industry

In America, the largest producers of sugarcane are Brazil with 39.15 million metric tons production per year, the United States with 16.5 million metric tons, and Mexico with 6.314 million metric tons. Colombia produced 2.25 million metric tons during the 2015/2016 period. Worldwide, Brazil is the largest producer of sugar, whereas Colombia is ranked at the 16th place on the list (United States Department of Agriculture [USDA] 2017c).

In Colombia, around 99% of the total production of sugarcane is located from the valley of the Cauca River to the south of the Department of Risaralda (Moncada et al. 2013). It is estimated that there are about 225,560 hectares planting sugarcane in the said region.

Figure 11.3 shows the behavior of the total production of sugar in tons, the amount of exports, and the national consumption. It is evident that there has not been a notable variation in the production of sugar mills from 2000 to 2016. Moreover, both the production and export of sugar have a similar behavior; however, it can be observed that the national sugar consumption has increased showing a moderate linear growth over the years. One of the possible reasons for this behavior is the growth of the national food industry.

Molasses is one of the major byproducts of sugarcane processing. It has been used as a product by other industries for ethanol production. Figure 11.4 shows the behavior of the production of molasses and its national consumption over time. As can be observed, both the production and consumption of molasses have a similar trend. Nevertheless, the national consumption was higher than the production in 2005. This can be explained because some sugar mills began to produce ethanol using molasses as raw material. Therefore, the national increase in ethanol production can be partially attributed to this fact.

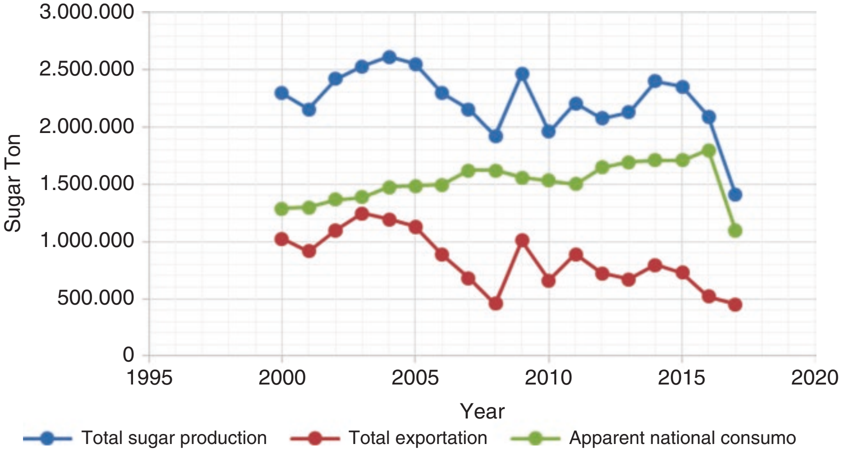

Fig. 11.3 Production, consumption, and export of sugar in Colombia ∗The data for 2017 are preliminary, subject to changes by the FEPA audit (Sugar Price Stabilization Fund). (Source: ASOCAÑA 2016a)

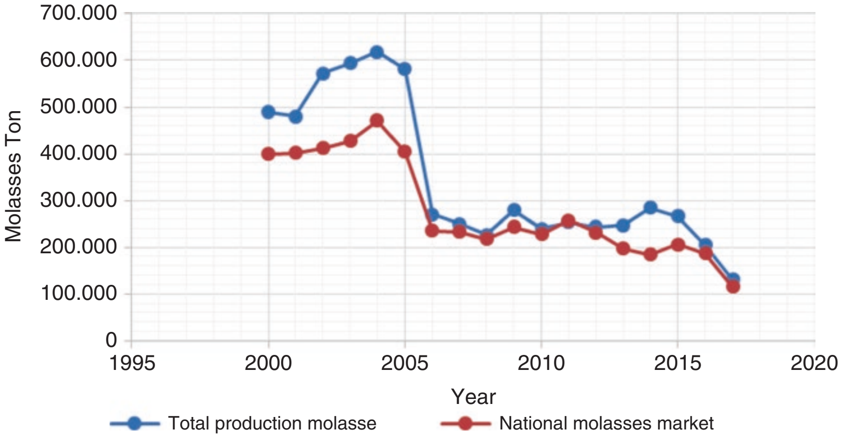

Fig. 11.4 Production and national market in Colombia ∗The data for 2017 are preliminary, subject to changes by the FEPA audit (Sugar Price Stabilization Fund). Source: ASOCAÑA 2016a)

The production of sugarcane bioethanol in Colombia began more than 10 years ago (since 2005). Currently, there are six bioethanol production plants, which produce around 450 million liters of ethanol annually. This trend would be attributed to public policies that sought to develop alternative sources of energy, paying attention to the environment and rural development. Five out of the thirteen mills have distilleries attached to the production of fuel alcohol including Incauca, Manuelita, Providencia, Mayagüez, and Risaralda. Figure 11.5 shows the ethanol production by the sugar mills.

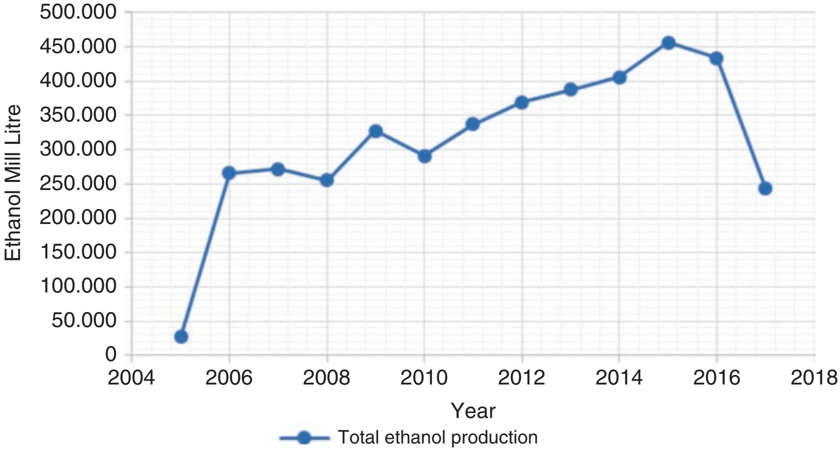

Fig. 11.5 Ethanol production in Colombia ∗The data for 2017 are preliminary, subject to changes by the FEPA audit (Sugar Price Stabilization Fund). (Source: ASOCAÑA 2016a)

11.6 Sugarcane Under the Biorefinery Concept in Colombia

The sugar industry in Colombia comprises a large number of companies, both public and private. Many of these firms use fermentation technology to obtain a range of products on an industrial scale. Major products of such companies include ethanol, yeasts, and different types of acids (e.g., citric and acetic acids). Moreover, these ventures also use molasses as a raw material to produce animal concentrate and fertilizer. Furthermore, bagasse is used to produce paper and agglomerates for generating steam to run mill turbines. Additionally, bagasse is also used for engendering electricity for mills' own consumption or for selling it to the electricity grid (Moncada et al. 2013).

Thus, the concept of biorefineries for sugarcane crops is widespread in Colombia, and many of the Colombian mills have adopted this concept to simultaneously produce sugar, fuel ethanol, and electricity, as described above. Manuelita is an example of a biorefinery in Colombia, in which the use and valorization of by-products is one of the main strategies.

11.7 Sugar Industry Market vs. the Biofuel Market in Colombia

Prices for sugar and ethanol have been quite stable over the years in Colombia in the past (Figs. 11.6 and 11.7). However, the prices for both of these products have shown slightly different tendencies in recent years. For bioethanol, a constant rise in the price per gallon is observed, whereas for sugar, a fluctuation in the price which declined in 2017 was seen.

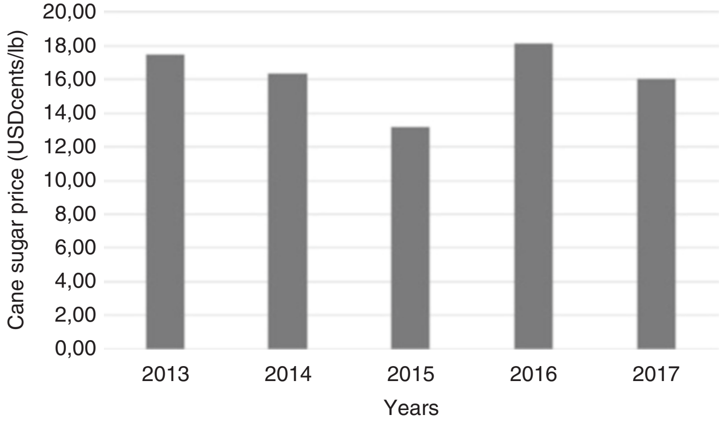

Fig. 11.6 Evolution of the international cane sugar price over last 4 years. (Source: ASOCAÑA 2016a)

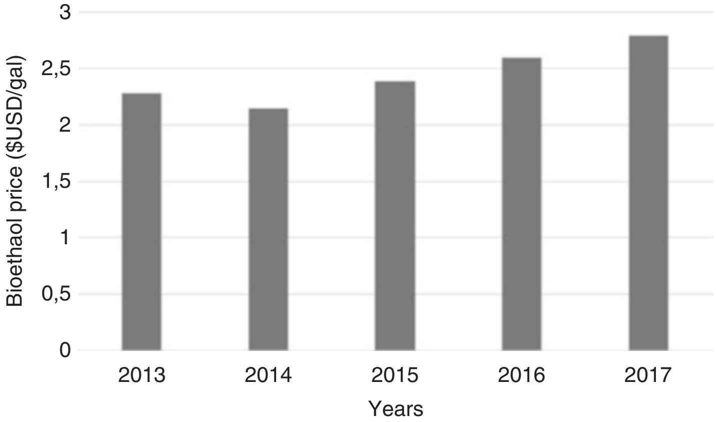

Fig. 11.7 Evolution of bioethanol price over last 4 years in Colombia. (Source: FedeBiocombustibles 2016)

In 2016, there was a constant decline in sugar prices worldwide (Fig. 11.8). According to ASOCAÑA, a surplus of approximately 2.18 million tons has been supplied over the last years. Moreover, different macroeconomic factors have affected the global sugar price and market (ASOCAÑA 2015). In fact, the national trading of sugar is ruled by the international behavior of economic indicators related to this product. Therefore, sugar mills commercialize sugar to companies that export their products based on the global price registered in international markets (Sánchez and Cardona 2007).

On the other hand, the national fuel market, which is regulated by political resolutions, influences the price of carburant alcohol. Even so, the Ministry of Mines and Energy has allowed the use of E10 blends in the country due to the development of new distillery plants in the Cauca valley (Rau and Gomez 2017). This has generated an increase in the demand and consumption of ethanol. Therefore, an increase in the price of alcohol was observed until 2016 (Fig. 11.9). Moreover, according to the Ministry of Mines and Energy of Colombia, for 2018, it was expected that it would be necessary to import bioethanol as the amount of ethanol available in the stocks was insufficient (MINMINAS 2017).

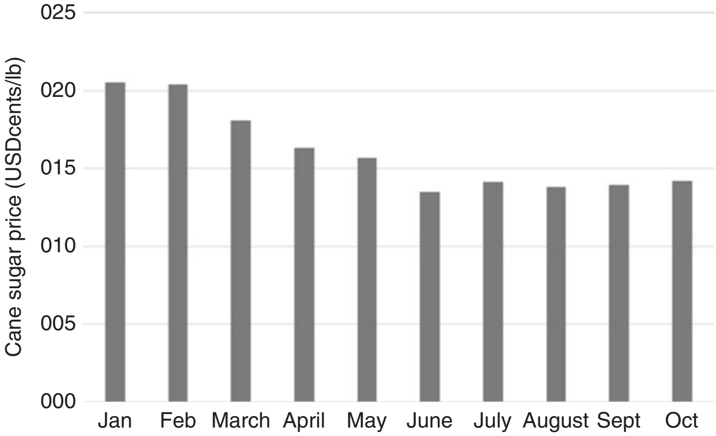

Fig. 11.8 Cane sugar price during the year 2016 in Colombia. (Source: ASOCAÑA 2016a)

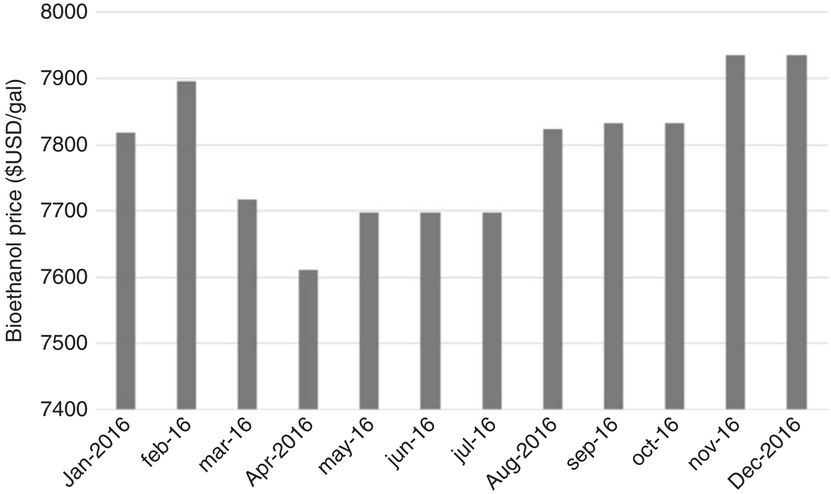

Fig. 11.9 Ethanol price during the year 2016 in Colombia. (Source: FedeBiocombustibles 2016)

11.8 Bioenergy Production from Sugarcane in Colombia

Accelerated climate change and high global energy demand require the adaptation of renewable and sustainable alternatives of energy. In addition, the decline of oil sources, the constant change in the price of fuels, and the current economic crisis are reasons to search for alternative sources to obtain renewable energy. Examples of biological materials to produce bioenergy can be cited as: wood, microbial biomass, livestock manure, and agricultural residues (Waclawovsky et al. 2010). According to El Bassam et al. (2013), there are many options to produce bioenergy from biomass: i) thermochemical conversion (combustion, gasification, and pyrolysis) to produce heat, electricity, and fuels; ii) biochemical conversion (digestion and fermentation) to generate electricity and fuels, and iii) extraction (e.g., from oilseeds) to yield fuels.

The annual energy generated in Colombia was approximately 6000 GWh per month in 2016 (Unidad de Planeación Minero Energética 2016). As indicated by the Inter-American Development Bank (IDB), the demand for energy by 2040 will be approximately 80% higher than the current one in Latin America. Among these countries, the fastest growing demand will be for Chile and Colombia, with an increase in consumption by 154.7% and 110.3%, respectively (Balza et al. 2016).

Sugarcane, mainly grown to produce sugar for the food industry in Colombia, is now also being used for bioenergy production (Tew and Cobill 2008). According to Chen and Chou (1993), the feasibility of sugarcane as an energy crop is because of its high yields per unit land area in tropical environments (50–150 tons of cane per hectare) with perennial growth. Additionally, sugarcane also presents a considerable portion of biomass (around 45–50% on a dry mass basis) that can be converted into fermentable sugars (Chen and Chou 1993). Based on the energetic potential of sugarcane, below are the most common applications that have emerged in the field of bioenergy from this crop in Colombia.

11.8.1 Sugarcane in Ethanol Production

In 2015, an ethanol production of around 27 billion gallons was reported worldwide (Renewable Fuels Associatio [RFA] 2018). The United States is the world's largest producer of ethanol from corn, having produced nearly 15 billion gallons in 2015 alone, followed by Brazil, which mainly uses sugarcane. In 2016, according to the Sugar Cane Growers Association of Colombia (ASOCAÑA), 430 million liters of ethanol was produced in Colombia.

For ethanol production directly from sugarcane (1G ethanol), sugarcane is harvested and milled. The juice (rich in sugars) is conditioned to make it more assailable by microorganisms during fermentation. From the fermented broth, the cellular biomass must be separated, to then carry out the separation of ethanol (distillation) and its subsequent dehydration through different unit operations obtaining anhydrous ethanol. This process can also use cane molasses, as well as other streams derived from the process of obtaining sugar in sugar mills (BNDES and CGEE 2008). The theoretical stoichiometric yield for this process is 0.511 g of ethanol and 0.489 g of CO_2, per 1 g of metabolized glucose. Considering the *Saccharomyces cerevisiae* yeast, it has been observed that experimental and industrial levels only reach between 87% and 95% of the theoretical yield (Vázquez and Dacosta 2007). However, for bacteria, *Zymomonas mobilis* reports have been very promising, providing high ethanol production of up to 97% of the theoretical maximum yield (Sánchez and Cardona 2008).

In order to improve productivity and counteract problems of inhibition, some stocks have been modified by genetic engineering. Additionally, there have been many investigations related to the integration and coupling of production stages to reduce costs and improve the efficiency of the process.

11.8.2 Biodiesel Production

In order to integrate processes, the ethanol production described above can be used, in situ, in the production of biodiesel by transesterification of oils. This is an interesting and attractive alternative as it can reduce energy and operational costs when the production of one of the raw materials is coupled with the same biodiesel facilities.

Biodiesel is a key liquid biofuel to establish the demand of the transportation sector. This biofuel can be blended and used in many different concentrations, and as an oxygenated biofuel, it can reduce particulate matter emissions (Guarieiro et al. 2014; Amaral et al. 2017). This renewable fuel is produced by transesterification of vegetable oils or animal fats with alcohol (methanol or ethanol), in the presence of a catalyst (e.g., sodium hydroxide) to produce monoalkyl esters (biodiesel) and glycerol (National Biodiesel Board 2017). The vegetable oils used for biodiesel production are rapeseed in European Union countries, soybean in Argentina and the United States, and palm and sunflower oils in Asia and Central American countries (Romano and Sorichetti 2011).

The advantages of integrating the transesterification process for biodiesel production with ethanol production in Colombia have been demonstrated by Gutiérrez et al. (2009), who studied the production of biodiesel from palm oil integrated with ethanol production from lignocellulosic residues and observed a reduction of 3.4% and 39.8% in unit energy costs, as well as material and energy integration, respectively.

11.8.3 Sugarcane as a Source of Butanol

In recent years, interest has been shown in obtaining butanol fermentation because it is an important chemical with many applications not only in biofuel sectors, but also in the production of solvents, plasticizers, butylamines, amino resins, butyl acetates, detergents, cosmetics, and vitamins (Donaldson et al. 2005). It has several advantages over ethanol as a fuel extender or fuel substitute. It has an energy content similar to gasoline; therefore, less volume is required than ethanol to achieve the same energy output. Butanol has a lower vapor pressure compared to ethanol and is therefore safer during transport and for using in car engines (Qureshi et al. 2013). Butanol can industrially be produced from petroleum or through fermentation using sugarcane, employing numerous *Clostridium* strains.

According to Donaldson et al. (2005), five to six billion tons of butanol are produced per year worldwide. Although currently Colombia is not producing any biobutanol, the production and demand in the world has grown dramatically over the last year, not only as biofuel, but also for other platforms. In 2017, imports of butanol in Colombia exceeded one million tons (Scavage 2018). On the other hand, there are expectations of the energy sector to analyze the convenience of butanol production from sugarcane and its subsequent blending with other fuels in the country. Biobutanol production has been studied mostly on the basis of microorganisms and fermentations at lab scale (Montoya et al. 2000; Jaramillo Obando and Cardona 2011).

The process for biobutanol production from lignocellulosic biomass starts with a pretreatment to hydrolyze the hemicellulose fraction, followed by an enzymatic hydrolysis of the cellulosic fraction. Then an alcohol-producing microorganism performs fermentation of the resulting sugars, and finally a separation step should be included, recovering the product of interest. According to the literature (Jeihanipour and Bashiri 2015; Qureshi et al. 2013; Ezeji et al. 2014; Qureshi 2014), two main phases, namely the acid production phase and solvent production phase, can be distinguished during the ABE fermentation by *Clostridium*.

The butanol production process is quite complex, which explains why biobutanol has not played a leading role compared to other petrochemicals. However, in recent years, due to rising environmental concerns and high and variable crude oil prices, interest in biotechnological production of butanol has renewed. Moon et al. (2015) studied butanol and isopropanol fermentation by *Clostridium beijerinckii optinoii* in 10 L batch fermentations. Mainly butanol (6.45 g L^{-1}) and isopropanol (3.45 g L^{-1}) were produced with very little ethanol/acetone (less than 0.2 g L^{-1}). Glucose was not completely consumed, with a sugar utilization of 81.7%, even after 90 h fermentation (Moon et al. 2015). In another study, Zhang et al. (2017) used sugarcane juice as a substrate, obtaining concentrations of 9.9 g L^{-1} butanol and 5.5 g L^{-1} butyrate. Colombia, as a promising location of sugarcane production, has the potential to exploit biobutanol in the biofuels sector.

11.8.4 Energy Cogeneration

Traditionally, biomass was burned to produce heat in the common combustion process. Generation and cogeneration technologies vary according to the type of biomass and the scale of the process. Gasifiers are used for direct heat application to produce higher value energy products such as electricity.

Bagasse has a gross calorific value of 19.25 MJ kg^{-1} at zero moisture and 9.95 MJ kg^{-1} at 48% moisture (Cardona et al. 2010). The fact that the same cane provides the energy for the production of sugar in the form of bagasse is a special characteristic of the sugar industry. Sugar mills will usually cogenerate enough to cover their needs. Nevertheless, the moisture content of sugarcane bagasse can affect both combustion and gasification efficiencies, resulting in operational problems during the processes.

According to Rincón et al. (2014), the biomass steam turbine technology (BST) is used to design biomass-fired cogeneration systems as the fuel source in the heat generation processes. However, biomass integrated gasification combined cycle (BIGCC) technology is an alternative technology.

11.8.4.1 Biomass Steam Turbine Technology

A heater, a dryer, a furnace, a steam turbine, and a water condenser comprise this system. After being dried, the biomass is burned at high reaction rates, and the released heat is enough to produce electricity and low-pressure steam that are used to supply part of the chemical process heating requirements (Iakovou et al. 2010; Rincón et al. 2014). Figure 11.10 shows the global process.

11.8.4.2 Biomass Integrated Gasification Combined Cycle Technology

A heater, divisor, compressor, gas turbine, dryer, integrated gasification and combustion system, heat recovery steam generator, water condenser, and a steam turbine are the components of this system, in which biomass is transformed into a fuel gas (Quintero et al. 2011; Rincón et al. 2014). Figure 11.11 shows the global process.

Deshmukh et al. (2013) obtained a net electricity generation potential of 170 kWh tc^{-1} and 140 kWh tc^{-1} for the BIGCC and the high-pressure steam Rankine cycle (advanced SRC, similar to BST), respectively. However, the advanced SRC system requires a bagasse feed rate of 50% less than the BIGCC system to meet the demand for low-pressure factory steam.

Energy cogeneration from sugarcane bagasse is a widely used process in the Colombian sugar industry. Normally, bagasse is burnt to generate steam and electricity (combined heat and power cycle—CHP), supplying the energy requirements of the sugar mill. The average electrical efficiency of bagasse-based power plants in Colombia is about 24%, while the CHP efficiency ranges between 45% and 65%

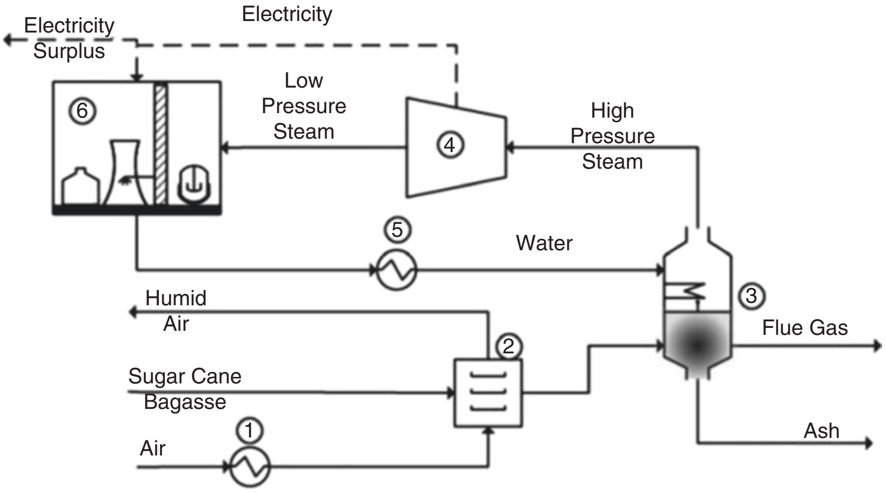

Fig. 11.10 Biomass steam turbine cogeneration system. (1) Heater; (2) dryer; (3) furnace; (4) steam turbine; (5) water condenser; (6) chemical process. (Source: Reprinted by permission from Springer Nature: Springer Nature, Rincón et al. (2014)), Copyright © 2013, Springer Nature (2013))

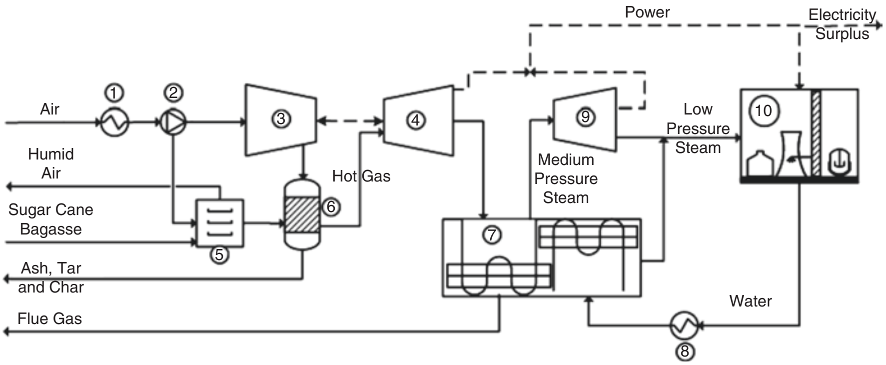

Fig. 11.11 Biomass-integrated gasification-combined cycle cogeneration system. (1) Heater; (2) divisor; (3) compressor; (4) primary gas turbine; (5) dryer; (6) integrated gasification and combustion system; (7) heat recovery steam generator; (8) water condenser; (9) secondary steam turbine; (10) chemical process. (Source: Reprinted by permission from Springer Nature: Springer Nature, Rincón et al. 2014), Copyright © 2013, Springer Nature (2013)

(Gauch 2012; Zah et al. 2012). In this context, in the country, there are around 21 cogeneration plants, with an installed capacity of approximately 400 megawatts; of which 60% correspond to sugar mills (Portafolio 2015). The sugar industry has developed the most bioenergy in the region; the cogeneration from sugarcane bagasse represented 30% of generation of energy in the Valle del Cauca region in Colombia during 2015 with 270 megawatts per hour of energy cogeneration (González 2017).

11.9 Capacity, Potential, and Future Perspectives

Demand for biofuels has been increasing over the past years, especially because global energy needs have increased by approximately 70% in the last 30 years. The transportation sector is one of the most significant sectors regarding energy consumption (Cortés-Marín and Ciro-Velázquez 2011). The main types of biofuels that are expanding their market are ethanol and biodiesel, especially the first-generation ones. Nonetheless, other forms are also growing, such as biogas and advanced biofuels, which are the fuels made from lignocellulose biomass or woody crops, agricultural residues, or waste or from nonfood cellulosic sources (Food and Agriculture Organization [FAO] 2008). The latter ones are more convenient than the first-generation biofuels because they are more sustainable, mainly because they diminish competition with food crops for using fertile soil and water, they have fewer problems related to greenhouse gas emissions, and they cause less negative effects on the biodiversity (Fiorese et al. 2013; FAO 2008). For example, according to the US Department of Energy, corn ethanol decreases greenhouse gas emissions by 28%, while the reduction for cellulosic ethanol is around 87% (Wang 2009).

Second-, third-, and fourth-generation biofuels have been studied as more sustainable alternatives to replace transportation fuels. Second-generation biofuels are harvested from lignocellulosic feedstocks such as sugarcane biomass, whereas third-generation fuels are those produced from algal biomass. The metabolic engineering of algae for the production of biofuels is considered the fourth-generation. It is the least known class of biofuels and is related to “carbon capture and storage” technologies to contribute toward reducing GHG emissions (Alam et al. 2012; Dutta et al. 2014; Hanney et al. 2012; International Service for the Acqusition of Agro-biotech Applications 2007).

Advanced biofuels have many barriers to overcome yet to be viable as they require advanced technical processes, more financial investments, and more research to simplify their production processes. Currently, second-generation is the category of advanced biofuels that have been extensively studied and is being commercialized (Hanney et al. 2012). Despite its advantages, second-generation biofuel production costs much more than a first-generation production system. According to Bracmort (2015), constructing a cellulosic ethanol plant that produces 30 million gallons per year (mgy) annually costs approximately US$ 225 million, while a plant of corn ethanol costs US$ 80 million to produce 40 mgy. Therefore, first generation is the main category of biofuels that is being produced around the world.

Ethanol dominates the world market as the first-generation biofuel, already becoming a valuable substitute for gasoline for transportation fuel (Sebayang et al. 2016). Its production in 2016 was about 120 billion liters and is expected to be 137 billion liters by 2026. Around 60% of its increase may originate from Brazil. The United States, China, and Thailand are other countries that are expected to contribute toward this expansion. Figure 11.12 shows the worldwide production of ethanol as reported by the Organisation for Economic Co-operation and Development and Food and Agriculture Organization (OECD/FAO 2017).

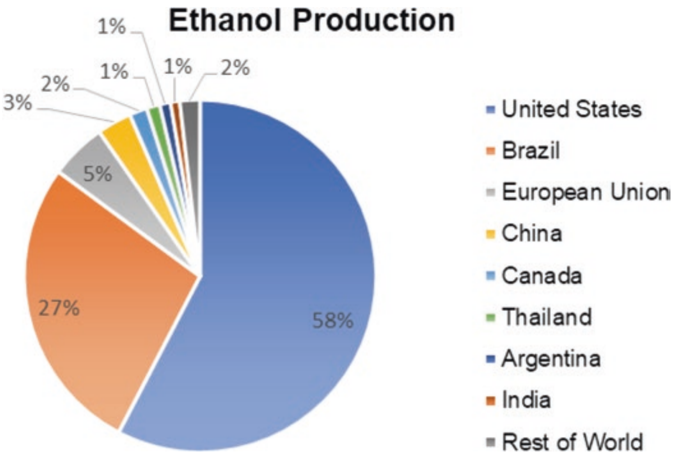

Fig. 11.12 Production of ethanol in the world. (Source: RFA 2017)

Concerning Latin America, Brazil is the leader in ethanol production, but other countries such as Colombia, Guatemala, Argentina, Paraguay, Jamaica, Peru, and Tobago also contribute significantly to its production. In Latin American region, between 2000 and 2008, the production of ethanol increased around 13% per year; in 2009, it declined by 3%; and between 2010 and 2011, the decrease was 17%. This considerable oscillation is associated to the increase in sugar prices, motivating the producers to focus on the sugar production instead of bioethanol (Bailis et al. 2014). It is expected that 20% of the global sugarcane production will be used to produce ethanol by 2026. The main sources for ethanol production in 2014–2016 and the prediction for 2026 are shown in Fig. 11.13.

As a first-generation fuel, bioethanol is produced from the fermentation of sugarcane juice and molasses, while the second-generation, cellulosic ethanol, is obtained from bagasse and straw generated in the plant during the 1G ethanol production process (Marin 2016). By 2026, approximately 35% of the global ethanol production will be based on sugar crops (OECD/FAO 2017). For around 100 countries, sugarcane is the most important crop in this reference; in 2015, 26.9 million hectares were used for its production, with a yield of 70.9 tons of fresh cane per hectare (FAO 2015).

Brazil and India are known as the main countries that use sugarcane as the most significant feedstock for ethanol (Sebayang et al. 2016). In 2017, the ethanol production in Brazil was 26.2 billion liters, and it is projected to increase to 36.3 billion liters until 2026. In the same period, India produced around 1.65 billion liters, 84% of which was collected from molasses (OECD/FAO 2017; USDA 2017a, b). Many countries in Latin America and Africa can also offer good prospects to increase sugarcane ethanol production to supply the biofuel demands (Fileni 2017).

Considering the financial perspective, the price of crude oil will likely double in the coming years, whereas the price of ethanol is predicted to remain stable. As a result, it will lead to reduction in demand for gasoline and an increase in the demand

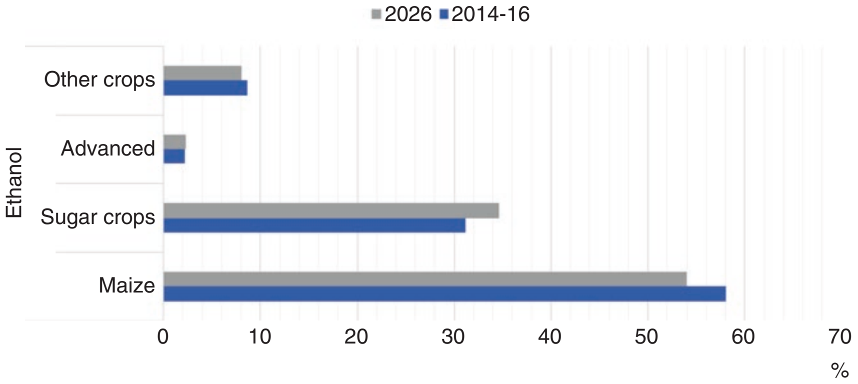

Fig. 11.13 Sources of ethanol production in the world. (Source: OECD/FAO 2017)

for ethanol in developed countries (OECD/FAO 2017). The production cost of ethanol depends on many variables, including geopolitical factors, the availability of raw material, and the required technology (Cortés-Marín and Ciro-Velázquez 2011). Ethanol from sugarcane has the lowest cost in comparison with any other source of ethanol (BNDES & CGEE 2008); therefore, sugarcane ethanol demands may rise considerably in the near future.

The ethanol trade is growing throughout the world and support policies for this biofuel are being adopted, for example: policies to replace the consumption of petroleum fuels with programs such as mandatory biofuel blends, reduction in taxes for biofuels, and policies that boost production domestically through local producer subsidies and import tariffs (International Trade Administration 2016; Kojima et al. 2007). According to Fileni (2017), Asia, a densely populated continent, contributes 58% toward global greenhouse gas emissions, and, consequently, ethanol is an attractive market to develop as a solution to this problem, particularly because it can be easily implemented. India, Indonesia, and the Philippines already have a mandatory mandate of ethanol blend. Africa also has a huge potential to supply ethanol as many countries harvest sugarcane, which can be used as ethanol feedstock.

In Latin America, we find countries with available and promising land, pioneer countries in terms of ethanol policies which make them attractive for investments in ethanol production, especially from sugarcane. A mandate ethanol blend is implemented in Argentina, Brazil, Colombia, Ecuador, Panama, Paraguay, and Peru (Bailis et al. 2014; Fileni 2017). Table 11.2 shows the countries from these three continents along with their ethanol blends.

According to Rau and Gomez (2017) and FedeBiocombustibles (2017b), estimates indicate that in 2017 Colombia produced 450 million liters of ethanol. This value was around 5% lower than previous years, mainly due to the weather phenomena “El Niño.” The ethanol production is supplied by seven ethanol distilleries; six plants are able to produce bioethanol almost year-round, and one additional ethanol facility called Bioenergy is managed by ECOPETROL with a current annual capacity of 60 million liters. This new ethanol plant, which started operating in 2016, has

Table 11.2 Ethanol blend in different countries

	Country	Status	Ethanol %
Asia	India	M	5
	Indonesia	M	1
	Philippines	M	10
	China	O	10
	Japan	O	3
	Thailand	O	–
	Vietnam	O	5–10
	Pakistan	UC	–
	Taiwan	UC	–
	Bangladesh	UC	–
Latin America	Argentina	M	12
	Colombia	M	8–10
	Costa Rica	M	7
	Ecuador	M	10
	Panama	M	10
	Paraguay	M	25
	Peru	M	7.8
	Mexico	O	2 (some cities)
	Uruguay	O	10
	Chile	UC	–
	Guatemala	UC	–
Africa	Angola	M	10
	Ethiopia	M	5
	Malawi	M	10
	Mozambique	M	10
	South Africa	M	2
	Sudan	M	5
	Zimbabwe	M	15
	Kenya	UC	10
	Mauritius	UC	–
	Nigeria	UC	–
	Zambia	UC	–

Source: Fileni (2017)
M mandatory, *O* optional, *UC* under consideration

already started adding 113 million liters of ethanol as it strives to hit its production capacity of 504,000 liters of ethanol per day in the short term (Wade 2017). Figure 11.14 shows the facilities' distribution in Colombia and their daily capacity.

It is important to highlight that there is no production of second- and third-generation biofuels in Colombia yet; only universities have conducted research on biofuel production from biomass. Furthermore, Colombia does not have programs to encourage storage or long-term stocks of biofuels. However, with the activities of

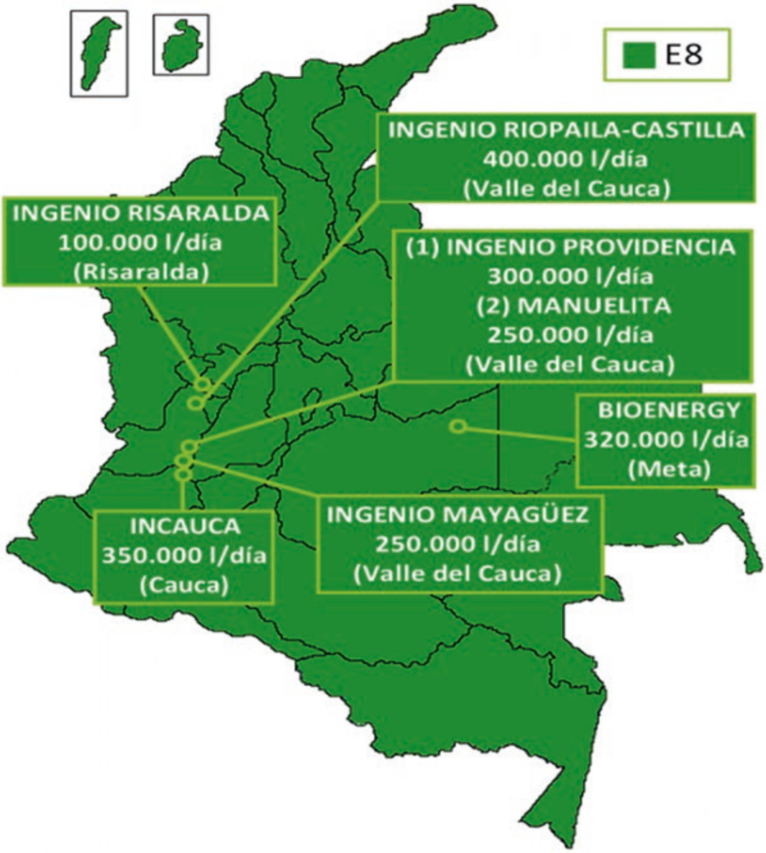

Fig. 11.14 Distribution of ethanol facilities in Colombia. (Source: FedeBiocombustibles 2017b)

the new plant (Bioenergy), an increase in ethanol production is expected, which should reduce the need to import ethanol to supply domestic demand, provided there are normal conditions for sugarcane production (Rau and Gomez 2017; ASOCAÑA 2017). The production of sugarcane ethanol in Colombia over the years is illustrated in Fig. 11.15.

It is expected that the future demand for biofuels in Colombia will be greater over the next few years to the extent that blending policies are increased. Currently, much of the country is at an E6 blend, while central Antioquia is at E8, and three regions bordering Venezuela do not have blending mandates while the country is looking to raise its ethanol-blending mandate to 10% (Cortés-Marín and Ciro-Velázquez 2011; PROCOLOMBIA 2018; Your Renewable News 2017). Because of a more efficient and coordinated public-private alliance, which promotes productivity and competitiveness, domestic demand for biofuels will have to be covered by increasing the ethanol production. The continuous increase in the production of

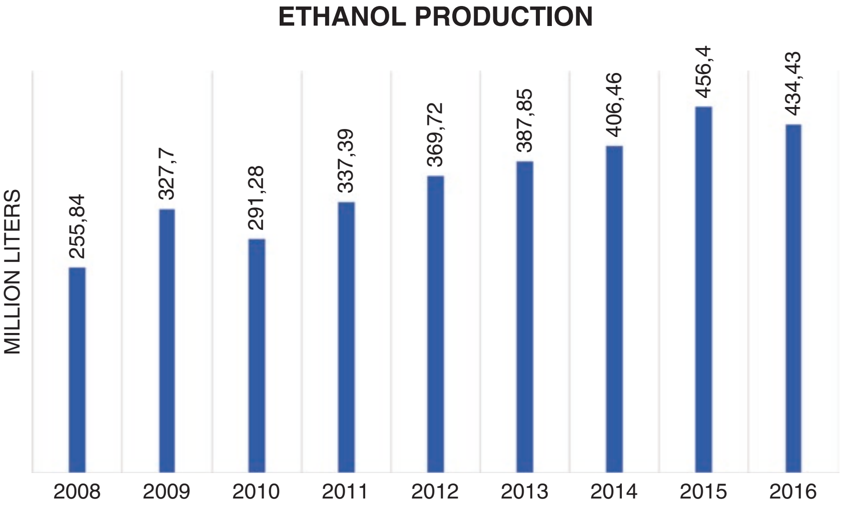

Fig. 11.15 Sugarcane ethanol production in Colombia. (Source: FedeBiocombustibles 2017b)

biofuels may even create a market for surpluses that could be exported (PROCOLOMBIA 2018; Rau and Gomez 2017).

11.10 Challenges in Sugarcane Energy Production in the Country

In recent years, one of the major challenges for most countries, including Colombia, is to establish energy policies that prioritize the reduction of fossil fuel utilization, increasing investments in renewable and green energy sources. In Colombia, especially in the valley of the Cauca River region, sugarcane is the biomass used as feedstock for bioenergy production, highlighting ethanol, electricity, and high-pressure steam (Colombo et al. 2014).

When compared to other countries, such as Brazil and the United States, bioenergy production from sugarcane in Colombia is still quite low, although the Colombian government and leaders from industries are aiming at rapidly expanding biofuel production to improve growth in rural areas (Cremonez et al. 2015; Gonzalez-Salazar et al. 2017).

As previously mentioned, biofuel production in Colombia, mainly ethanol, is done in small mills and “trapiches”, and a highly vertically integrated industry with only a few companies that manage the whole production and sugarcane processing. Thus, another challenge is to transform the small producers into large-scale industries and/or biorefineries and implement more mechanized methods for sugarcane harvesting, which is difficult because of the fear of generating mass unemployment.

Bioethanol producers also do not have a well-established biofuel distribution chain, and consequently they need to use indirect channels. Therefore, it is a great challenge for the bioethanol industry to offer a direct distribution chain because producers must be ensured that the products will be transported and sold, maintaining the quality standards required by the industry and the consumers. Hence, it is necessary to create specific distribution and commercialization chains for biofuel industries due to the particular characteristics of this market with growing demands (Ramírez-Velásquez et al. 2012).

It is imperative for Colombia to encourage R&D technology programs that generate bioproducts at competitive levels for local demands in the short and medium term and, for exportation in the long-term, diversifying its raw material. The Colombian government, more specifically the Ministry of Agriculture, has signed partnerships with other countries, e.g., the Netherlands, to develop projects that aim at investigating practical and political tools for implementing the sustainable use of bioenergy (The Netherlands Programmes for Sustainable Biomass 2013). It is also necessary to implement government policies for agricultural expansion and support of the sugarcane industry to ensure sustainable development avoiding environmental damage due to deforestation for expansion of sugarcane-planted areas, as well as the indiscriminate use of herbicides and other chemical products (Toasa 2009).

The use of sugarcane bagasse and straw (by-products of sugar and 1G ethanol processes) as feedstock for 2G ethanol production in mills can increase the environmental friendly production of bioethanol. Enhanced output of bioethanol can be realized by using new technologies that achieve maximum utilization of different raw materials (Rosillo-Calle and Walter 2006; Ramírez-Velásquez et al. 2012). Moreover, new laws on the mandatory blend of ethanol in gasoline and tax incentives have been used to expand the energy industry from sugarcane (Gonzalez-Salazar et al. 2017). In the coming years, almost all the sugar producers from the valley of the Cauca River will have an ethanol and biomass cogeneration plant. According to Colombia's National Biofuel Federation (FedeBiocombustibles 2017a), there are programs to attract investors and further expand the growth of the biofuel industry in Colombia by following stricter environmental rules and using new varied crops that can be more climate-adapted.

Fedebiocombustibles and ASOCAÑA also hope to attract growers to the East and North of Colombia, and Ecopetrol, the largest oil and gas company in Colombia, is developing a major biofuel project also in the East of the country. Additionally, this industrial sector has attracted substantial foreign investment from Israeli, American, and Brazilian companies (Gronewold 2011).

The bioethanol market could be economically competitive and shows environmental benefits as using biofuels reduces greenhouse gas emissions, and therefore it has higher sociopolitical acceptance. However, there is a need to increase the incentives to use biofuels, such as introducing the mandatory use of non-fossil fuels or less polluting fuels, along with punitive measures that protect the environment. In this regard, the Colombian government has played an important role in generating a biofuel blend program, establishing technical standards for the transportation of bioethanol, implementing market studies on biofuels, and diversifying its energy matrix (Rodado 2011).

11.11 Conclusions

In recent years, environmental concerns about fossil fuels are being mitigated by adopting renewable energy sources. Consequently, biofuels have become the focus to supply the world's energy demand. Sugarcane is an important biomass used for bioenergy production. Colombia is the seventh largest grower of sugarcane. The country has excellent agro-climatic conditions for sugarcane cultivation in its valley of Cauca River, where most of the cane farming and sugar industry is located. Colombia is using E6 ethanol blend, and plans to enhance its blending mandate to 10%. In order to further increase the ethanol production from sugarcane, it is important to have more capital investments associated with socioeconomic and environmental planning for renewable energy production.

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Chapter 12
Environmental, Economic, and Social Impacts of Biofuel Production from Sugarcane in Australia

Nanjappa Ashwath and Zobaidul Kabir

12.1 Background

Sugarcane is one of Australia's largest crops and is grown over 565,000 ha (Agrifutures 2018; Commonwealth Australia 2010; Fig. 12.1). Sugarcane cultivation supports the production of raw sugar, ethanol, and green energy. Currently, around 4000 cane farmers grow sugarcane mostly on family-owned farms. The existing infrastructure such as mills, cane tramways, sugar export terminals, and water supply schemes for irrigation support the production of sugarcane leading to economic growth in the region (Department of Agriculture, Fisheries and Forestry 2013). It is expected, under the current demand for sugar worldwide, further significant expansion of sugarcane industry is possible, particularly through tropical Queensland, Western Australia, and the Northern Territory.

The sugarcane industry's major product is raw crystal sugar, which is sold to refineries both in Australia and abroad. Approximately 95% of Australian raw sugar is produced in Queensland with the rest from Northern New South Wales. Up to 35 million tons of sugarcane is grown each year. Over a season, the sugarcane crop can produce up to 4.5 million tons of raw sugar, one million tons of molasses, and ten million tons of bagasse (a fibrous cane residue that fuels boilers to cogenerate steam and electricity). Approximately 85% of the raw sugar produced in Queensland is exported, generating up to $2.0 billion in export earnings for Queensland (Australian Sugar Milling Council [ASMC] 2018).

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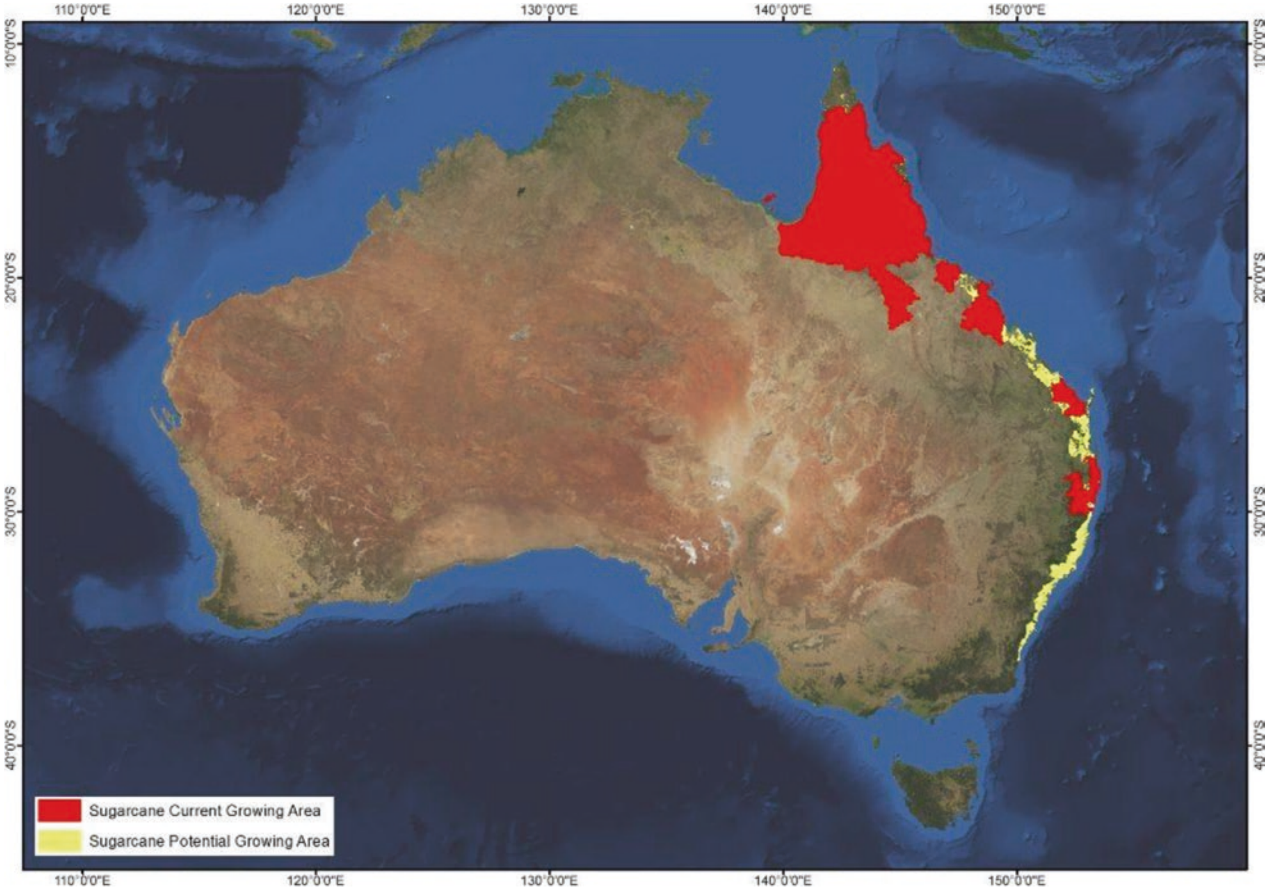

Fig. 12.1 Sugarcane production areas in Queensland and NSW. (Source: Agrifutures 2018)

Since sugarcane cultivation spans over such a large area (2200 km), its production is subject to various climatic and socioeconomic pressures. This chapter reviews some of the issues associated with sugarcane cultivation for sugar and bioethanol production.

12.2 Sugarcane Cultivation in Australia

Sugarcane farms are established through stem cuttings in Australia (setts/billets). Setts are planted in rows of 1.5 m and the crop is fertilized, often irrigated (40% of farms) and sprayed with herbicides (Fig. 12.2). The crop is harvested within 10–18 months of planting, mostly from June to December. One planting will last for 3–5 crop harvests. Australians have pioneered in cane harvesting technology and adapt "green cane" or "burnt cane" approach. In green cane harvesting, the cane is harvested along with the leaves, with the disposal of the leaves and the tops in the field. In burnt cane approach, the leaves are burnt and the stem is harvested. Cane harvesting is done mechanically using self-propelled harvesting machines to produce billets (or cut stems). The billets are loaded onto trucks or trains for delivery to the mills within a day or two. The farmer is paid according to the "cane payment system" which relies upon sugar content and the weight of the cane supplied (Sugar Notes 1997).

In the last 75 years, advances in sugarcane research have allowed the cane growers to maximize cane yields from 40 tons to 80–100 tons ha^{-1}. These advances

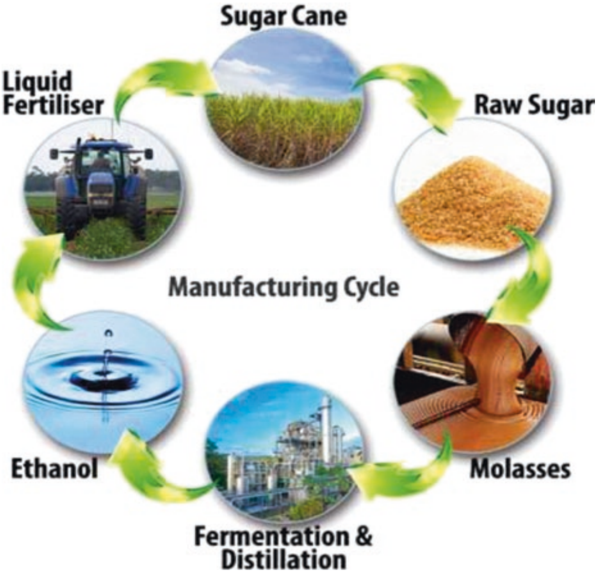

Fig. 12.2 Sugar and ethanol production cycle from sugarcane. (Source: Ethanol Facts n.d.)

include development of new cultivars (currently 70 cultivars are used), improved agronomic practices, pest and disease control, and harvesting and marketing technology (ASMC 2018). Long-term sustainability and reduction of adverse environmental impacts are the two important issues that bother sugarcane industry in Australia. Although sugarcane is a greenhouse gas neutral crop, it is a hungry crop requiring copious amounts of water and nutrients to achieve its maximum yield potential. Farmers will have to keep up with these inputs to achieve maximum yield. Application of heavy doses of fertilizers onto sandy to silty loam soils results in leaching of nutrients into creeks, rivers, and finally the Great Barrier Reef (Thornburn et al. 2011).

Several environmental programs are currently underway to find the means of minimizing nutrient leaching into the GBR, with the view to protecting the world-renowned natural heritage. The Australian government is spending millions of dollars to develop sustainable practices for sugarcane production. Some of these practices include new farm management practices, chemical accreditation training, water quality monitoring, trickle irrigation, integrated pest management, soil conservation, and restoration of wetlands and river banks. Promotion of green cane harvesting technology has helped immensely to minimize adverse environmental impacts (Duffy 2012).

12.3 Sugarcane Processing

Sugarcane production and its use in synthesizing various products are illustrated in Fig. 12.2. Once harvested, sugarcane must be milled within 16 hours to minimize degradation. Thus, cane crushing occurs 24 hours a day and 7 days a week for up to 22 weeks in a year. Australia has developed the most advanced technology to process sugarcane, and this technology is exported to other cane-growing countries as well. Sugar manufacturing begins with the shredding of billets to produce sugar juice and bagasse. The juice is pumped for further processing, and the bagasse is recycled as a fuel for the boiler (Khan et al. 2017). The juice is treated with lime and heated. This process results in clear juice and filter mud (dunder). The clear juice is concentrated by boiling to produce syrup. The syrup is again boiled and crystallized. This process is repeated, and the uncrystallized syrup is removed as molasses. The filter mud is used as a fertilizer, as it contains high concentrations of phosphorus. Molasses are either exported or used as stock feed. They are also used in distilleries to synthesize industrial alcohol (ethanol), rum, and carbon dioxide.

Sugar manufacturing results in a variety of by-products. These include bagasse, filter mud, and molasses. Bagasse is used as a source of fuel and it adds 20 megawatts of power to Queensland's electricity grid (Bioenergy Australia 2018). The ash and filter mud are used in sugarcane cultivation, and hence they will return some proportion of the nutrients removed from the cane fields (Sugar Notes 1997).

12.4 Potential of Ethanol Production

Ethanol produced from sugarcane has the potential to meet a very significant proportion of Australia's current automotive gasoline requirements. In a possible moderate ethanol production scenario that includes trash collection and cellulosic ethanol production, sugarcane has the potential to provide sufficient ethanol to meet 14% of Australia's (or 61% of Queensland's) automotive gasoline requirement while not consuming any additional coal or other supplementary fuels (Global Agricultural Industrial Network [GAIN] 2017). Through crop expansion or the coprocessing of other renewable fibers (such as sweet sorghum or green waste), further ethanol production may even be possible. Higher ethanol production quantities are also possible with the cultivation of higher biomass sugarcane varieties and the cultivation of varieties with a higher proportion of total fermentable sugars (GAIN 2017). According to the Audit report by the Queensland Department of Agriculture, Forestry and Fisheries, Queensland has the potential to increase the land use for sugarcane from 0.33% to 4.06%. This means in Queensland, there is an enormous opportunity for growing sugarcane. Based on the technology of using waste resources for growing algae, cane growing and sugar processing can also occur to produce biofuels (Prasad et al. 2014).

12.5 Refineries

Bioethanol production mostly occurs at three major refineries in Australia (Bureau of Resources and Energy Economics 2014). These facilities are located in Queensland (Sarina and Dolby) and NSW (Nowra). Australia produces 1.3 million tons of refined sugar annually, which is used nationwide or exported (ASMC 2018; Bioenergy Australia 2018). In 2012, Australia produced 440 million liters (ML) of ethanol. Around 68% of this occurs in NSW and is produced from waste wheat starch. The Dolby refinery uses sorghum to produce 80 ML of ethanol from sorghum. The Sarina refinery uses molasses from sugarcane and it generates 60 ML of ethanol annually (Rural Industry Research and Development Corporation [RIRDC] 2018). Sarina refinery is ranked as the most energy-efficient refinery in Australia, as it uses sugarcane bagasse as the energy source for ethanol production (co-generation) (Farrell 2014). An additional 90 ML of ethanol could be produced, if all exported cane molasses produced in Queensland could be used in ethanol production (O'Hara 2010). In 2017, the total biofuel production in Queensland alone was 290 million liters, including 250 million liters of ethanol and 40 million liters of biodiesel.

12.6 Policies and Regulations

In Australia, ethanol is blended into regular petroleum products and marketed as E10 (10% ethanol) which is currently mandated in Queensland and New South Wales (NSW). In 2001, the Australian government tried to introduce voluntary national biofuel target of 350 ML per annum by 2010. The Queensland government then attempted to introduce 5% ethanol (on average), but this bill was rejected in October 2014 due to uncertainty in fuel excise regime.

Later, Queensland passed the Liquid Fuel Supply (Ethanol and Other Biofuels Mandate) Amendment Bill in December 2015, according to which 3% ethanol was mandated for all petrol sold in Queensland. This became effective from January 1, 2017, with the intention of increasing the mandate to 4% ethanol after 18 months (Department of Natural Resources Mines and Energy 2015). For example, if 4 out of every 10 liters of regular petrol sold by a petrol station (or group of petrol stations) were E10, which contains 10% ethanol, the fuel retailer would have complied with the bio-based petrol mandate. A key objective of this amendment of course was to deliver a net greenhouse gas benefit compared to regular fuel. It was expected that more motor vehicles would use petrol with ethanol and thereby reduce the greenhouse gas emission. In addition, petrol stations were advised to take necessary action to make available ethanol-mixed petrol to drivers.

The government rebates have been introduced to promote biofuels in Australia. For example, federal government introduced Ethanol Production Grants (EPG) in 2008. This program provided a rebate of 38.143 c L^{-1} fuel excise for domestically produced ethanol used in the transport sector. The EPG was introduced to protect local ethanol industries against cheap imports and to encourage the community to use ethanol as an alternative transport fuel (Australian Government Department of Industry 2014). However, bioethanol production declined by 17%, despite the EPG scheme. The EPG program was finally closed in June 2015. Simultaneously, the excise was also removed for 1 year. From July 2016, the fuel excise was increased by 6.554% each year until it reaches 12.5 c L^{-1} in July 2020 (Biofuel Association of Australia 2014). At this stage, a subsidy of 25.643 c L^{-1} will be provided while the imported fuel will still be subject to an import duty of 38.143 c L^{-1}.

12.7 Other Feedstock Options for Australia

Second-generation biofuels such as energy crops and algae-based fuels have been successfully demonstrated, but there is no commercial production, and no subsidy schemes are being offered for commercial sales. A significant research effort has been initiated by a number of research agencies in the development of first-generation and second-generation biofuels (RIRDC 2018). The Queensland government has recently announced a number of programs aimed at making the state a center of biomanufacturing and biofuel production. It also hopes to develop the commercial production of biofuels for military, maritime, and aviation uses (GAIN 2017).

In addition to sugarcane, other lignocellulosic biomass is considered for bioenergy production, including forest residues of both hardwood and softwood timber which form number one significant source (e.g., eucalypt and pine residues). Agricultural wastes such as sorghum straw, rice straw, wheat stubble, corn stover, and sugarcane bagasse (O'Hara 2010) are also used. Furthermore, cultivation of perennial grasses such as Napier grass (*Pennisetum purpureum*), *Miscanthus* sp., and giant reed (*Arundo donax*) is investigated exclusively for biofuel production.

Australia has diverse climatic conditions ranging from temperate to subtropical and tropical climates. Region-specific species must be tested for biofuel production. Consideration should also be given to using native species such as brigalow and the exotic weeds (e.g., camphor laurel, *Mimosa pigra*, and *Acacia nilotica*) that use low water and nutrients (1200 mm of seasonal water and a nitrogen requirement of 120 kg ha^{-1} yr.$^{-1}$). The highly water-use-efficient plant such as agave is also being field-tested for bioethanol production (Holtum and Chambers 2010; Rijal et al. 2016a, b).

12.8 Impacts of Biofuel Production from Sugarcane in Queensland

One of the primary justifications for a shift to biofuels as an alternative source of energy has to do with climatic benefits that are anticipated to occur from the substitution of fossil fuels whose combustion results in large net greenhouse gases emission (German et al. 2011). Of the possible sources of bioethanol, sugarcane crops are the most land-efficient crops in replacing fossil energy, and here in tropical Queensland, sugarcane significantly outperforms sugar beet grown in temperate regions, as it produces up to 8 units of energy per unit of petrol energy used (Wikipedia Contributors 2018).

Although biofuel production remains small in the context of total energy demand in Australia, it is significant in relation to current levels of agricultural production. The potential environmental and social implications of its continued growth must therefore be recognized. The reduction of greenhouse gas emissions are among the explicit goals of some policy measures to support biofuel production. Unintended negative impacts on land, water, and biodiversity count among the side effects of agricultural production in general, but they are of particular concern with respect to biofuels, for example, the production of bioethanol and biodiesel from sugarcane. The extent of such impacts depends on how biofuel feedstocks are produced and processed, the scale of production, and, in particular, how they influence land-use change, intensification, and international trade (Food and Agricultural Organization 2012).

12.9 Impacts on Climate Change

One of the primary justifications for a shift to biofuels as an alternative source of energy has to do with the climatic benefits that are anticipated to occur from the substitution of fossil fuels, whose combustion results in large net emission of CO_2, to fuels whose combustion gases are sequestered through cultivation and thus are considered as greenhouse gases (GHGs) neutral (Macedo et al. 2008; Peters and Thielmann 2008). This promise of greener energy for transport has led to the inclusion of biofuels in alternative energy targets in many industrialized countries, notably the USA and the EU, Australia, Canada, and a growing number of developing countries, notably Brazil (Petrolworld 2008).

Ethanol-blended fuels have been shown to produce lower concentrations of GHG than fossil fuel, proving to be a superior, more sustainable fuel in the long term, and thus encouraging the introduction of even more blend combinations to the market (Department of Environment and Energy 2018a). The government reviewed its climate change policies in 2017 to ensure low emission in various sectors including electricity sector. It is to be noted that Australia's emissions for the year to March 2018 were 1.9% below the emissions in 2000 (547.0 Mt. CO_2-e) and 11.2% below the emissions in 2005 (604.7 Mt. CO_2-e). Electricity sector emissions have declined by 13.9% (29.2 Mt. CO_2-e) in the year to March 2018, from the peak recorded in the year to March 2009 (Fig. 12.3). At the same time, emissions per capita were at their lowest levels in 28 years. Emissions per capita in the year to March 2018 have fallen 36% since 1990 (Department of Environment and Energy 2018a).

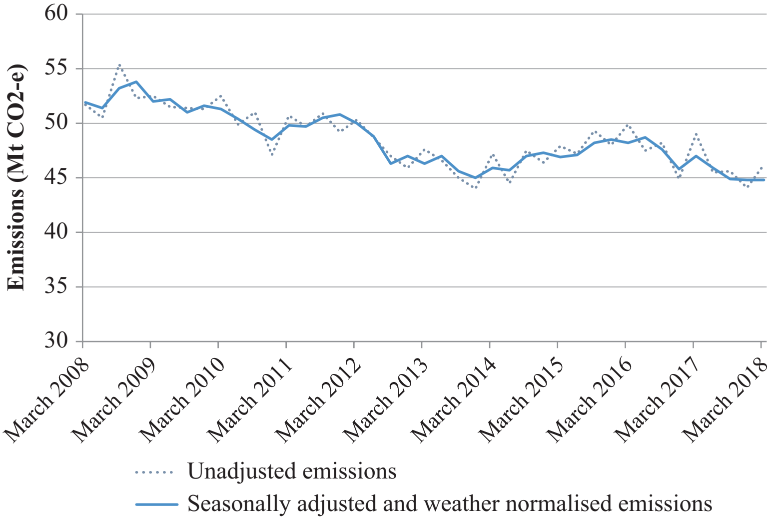

Fig. 12.3 Emission from electricity sector by quarter, Australia, from 2008 to 2018. (Source: Department of Environment and Energy 2018a)

The emission projections show that Australia continues to make progress in reducing emissions (Fig. 12.3), for example, in the electricity sector. Considering the climate change, the government is gradually reducing reliance on coal and increasing renewable generation. The renewable energy generation, for example, has increased by 12% in 2015–16, comprising 15% of total generation in Australia. Renewables continued to grow strongly in the calendar year 2016, to reach more than 16% of total generation. Although other sources such as hydropower and solar are the main sources of renewable energy, the production of biofuels in Australia as a whole and the Queensland state in particular is increasing. Among all the states in Australia, biofuel generation in Queensland is higher than in any other states (Department of Environment and Energy 2017).

In Australia, the transport sector requires more than 1.4 billion liters of fuel each year. The government had intended to produce at least 5% of the total transport fuel from biomass together with the net reduction of 3.5 million tons of carbon from Australia's net annual GHG emission. The emission of GHGs in CO_2 equivalent from the total petroleum fuel production and fuel use in Australia is approximately 120 million tons each year (Department of Environment and Energy 2017).

Bioethanol produced from sugarcane is environmentally friendly, particularly concerning the reduction in GHG (NO_x, SO_x, CO_x) emission. The use of bioethanol to reduce NO_x is attractive for several reasons. First, bioethanol contains little nitrogen, as compared to the diesel fuel. Second, bioethanol contains virtually trace amount of sulfur, so SO_x emissions are also decreased in direct proportion to the petro fuel replacement. When a petro fuel is replaced by a biofuel, there is a net reduction in CO_x emissions also (Demirbas 2009). It is estimated that bioethanol can save 41% (Tilman et al. 2006) to 52% of GHG emission as compared to petroleum-based fuels. Bioethanol is also known to reduce particle mass emissions by 57% (United States Department of Agriculture [USDA] 2017).

12.10 Biophysical Impacts

While biofuel potentially reduces GHG emissions, some studies suggest that the emissions associated with direct and indirect land-use change alone may negate estimated climatic benefits, particularly when biofuels displace carbon-rich ecosystems and effect food production (Lapola et al. 2010; Pleven et al. 2010). Within scientific and policy circles, it is increasingly recognized that adequate accounting of the effects of biofuels must consider the full life cycle of the bioenergy production, distribution, and consumption chain, as well as direct and indirect land-use changes associated with biofuel feedstock cultivation (Fritsche et al. 2011; Pena et al. 2010).

In the context of Queensland, the effect of sugarcane cultivation in the surrounds of Great Barrier Reef (GBR) has been a great concern (Waterhouse et al. 2012). Most of the sugarcane fields in Queensland are situated along the GBR catchment area. The chemical Diuron is widely used in the GBR catchment as a herbicide and has been described as essential for growing tropical crops like sugarcane (Duffy 2012). The sugarcane industry is the third largest user of Diuron in Australia, and this crop is largely grown in the GBR catchment (Holmes 2014a, b). Diuron is particularly damaging to the GBR and has been detected within the catchments and waters of the GBR. When released into waters, Diuron can reduce the ability of the coral ecosystems to photosynthesize. Diuron has also been shown to have adverse impact on sea grasses, mangroves, corals, and other species (Jones et al. 2015).

Other sources of agricultural pollution in the GBR region include the use of herbicides like atrazine and hexazinone and the increased use of fertilizers containing nitrogen and phosphorous. Dissolved inorganic nitrogen (DIN) from sugarcane farming is particularly a significant problem (Waterhouse et al. 2012). DIN is released from many regularly used fertilizers, and it increases organic matter in the planktons and sediments leading to higher outbreaks of coral disease and the invasive "crown of thorns starfish" (Waterhouse et al. 2012). DIN from the three *priority catchments* was recently reported to be the number one priority pollutant affecting water quality in the GBR (Davis et al. 2013).

It is to be noted that 85% of sugarcane production in Queensland is concentrated in three catchment areas: the Wet Tropics, Burdekin Dry Tropics, and Mackay-Whitsunday regions (Smith et al. 2014). These are often referred to as the "priority catchment areas." A study conducted in 2012 found that the use of nitrogen fertilizers in these three areas was a top priority for policy management to address (Waterhouse et al. 2012). Furthermore, sugar mills produce waste water, emissions, and solid waste that impact on the environment. The massive quantities of plant matter and sludge washed from mills decompose in freshwater bodies, absorbing all available oxygen leading to massive fish kills. In addition, mills release flue gases, soot, ash, ammonia, and other substances during processing (Waterhouse et al. 2012).

Another issue of concern is the fact that land laid bare in preparation for cane planting is stripped of any protective cover, allowing the soils to dry out. This affects microbial diversity and mass, both of which are essential to maintain soil fertility. Additionally, exposed topsoil is easily washed off from the sloping land, with nutrients leached from the topsoil. Furthermore, the continual removal of cane from the fields gradually reduces fertility and forces the growers to rely increasingly on fertilizers (Puri et al. 2012). In general, production of ethanol would provide greater benefits if their biomass feedstocks can be produced with reduced inputs (i.e., less fertilizer, pesticide, and energy), were producible on land of low agricultural value, and required low input energy to convert feedstocks to biofuel (Puri et al. 2012).

Akbar et al. (2018) list factors that limit commercial production of ethanol: (i) additional pressure on prime agricultural land, (ii) food vs fuel and biodiversity issues, (iii) adverse environmental impacts, and (iv) costly feedstocks. They also stated that inconsistency in the support of both federal and state governments also curtail the commitment of entrepreneurs who endeavor to invest in biofuel production facilities. For example, NSW government has mandated 6% bioethanol and Queensland government 4% ethanol (Fair Trading NSW 2015; USDA 2017). However, the other states have not shown support. It is also uncertain if the above mandates would be changed with the changes in the ruling parties of the governments, as has occurred in the past. Lack of government subsidies to start large-scale production plants is another constraint for promoting bioethanol production in Australia. The lack of Australian Government's action to penalise the fuel companies those fail to comply with the mandated bioethanol use is an important issue. This is discouraging the entrepreneurs who are keen to invest in biofuel production facilities.

A reef protection regulation was introduced by the Government of Queensland recently to ensure best practice farming by sugar industries and thereby protecting the biophysical impacts. There are a number of programs and support tools that help cane farmers adopt best farming practices. The government has initiated "*The Smartcane Best Management Practice (BMP)" program* which is an industry-developed, robust, and practical system that deals in improving productivity, profitability, and sustainability of farm enterprises. Through the Smartcane BMP, cane growers self-assess their practices to determine if they are "below," "at," or "above" the industry standard. Adopting practices for effective nutrient management can improve farm productivity and profitability, and reduce nutrient losses to the reef (Queensland Government 2018). It is expected that cane farming biophysical impacts will be reduced, thereby adding more value to the GHG reduction.

12.11 Social Impacts

In addition to environmental impacts, it is equally important to analyze the trends of social impacts of sugarcane ethanol industry. The study on the life cycle analysis of ethanol indicates that there are various social impacts that affect more than one group of actors. These issues, which are crucial in the debate surrounding the social sustainability of sugarcane in general, include energy security, compliance with legal framework, law enforcement, employment and income generation, public participation, public acceptance of biofuel, and health impacts. Energy security constitutes one of the main driving forces behind the biofuel development policies in Australia and elsewhere in the world (Rossi and Hinrichs 2011; Selfa et al. 2011) as one of the benefits of biofuels would be to reduce dependence on foreign energy at the national level (Sobrino et al. 2010). In addition, there is evidence that biofuel production has increased energy security at the household level and local level through the implementation of small-scale projects (Gasparatos et al. 2011).

Landholders surrounding sugarcane fields and particularly fishermen who depend on fishing for livelihood can be affected adversely, leading to loss or reduction of income. Social inequality may arise at local, regional, and national levels. There need to be a strong and comprehensive regulation and guideline to address these social issues in biofuel as well as the ethanol sector (Sawyer 2008). The cumulative negative social impacts of the ethanol industry could damage its social-political legitimacy (Hall et al. 2011), if there is not a sturdy legal framework for biofuel development and active law-enforcement mechanisms. However, one of the positive social impacts is that the development of biofuel programs can create jobs in rural areas, and along the overall productive chain, from research to trade and services (Neves 2010).

The role played by the bioethanol and biodiesel productions in job creation in Queensland has not yet been determined comprehensively. However, evidences show that labor forces are required from sugarcane production to biofuel synthesis and its marketing. In Australia, ethanol industry is usually characterized by centralized, large-scale, and export-driven production. This model is less labor-intensive since it is based on mechanized harvesting and involves higher rates of temporary, unskilled employment at the farm level (German et al. 2011). In Brazil, for example, one single machine in sugarcane harvesting can displace 80 workers (Smeets et al. 2008). However, temporary jobs are created during the construction of the processing plant, while jobs at the refinery would demand unskilled and highly skilled laborers (Bell et al. 2011).

Community acceptance and community engagement are other issues of social impacts in the biofuel sector. Community acceptance of biofuels varies among different geographical contexts, and previous studies do not offer conclusive results on the subject, particularly in the context of Queensland. This requires study of the community acceptance on ethanol production. A study on the stakeholders' perception about sugarcane industry indicated that the stakeholders (farmers) were not interested in engaging their next generation in the sugarcane sector. With this in view, ethanol production could face public resistance in the future, if technology does not advance as forecasted, that is, developing cellulosic ethanol with improved cost and environmental efficiency (Luk et al. 2010). Consumer acceptance of ethanol or biodiesel depends mainly on the price and supply stability.

Communities surrounding the sugarcane fields may be concerned about a number of aspects such as changes on aesthetics, concentration of incomes by large-scale firms, and feedstock transportation constraints among others (Rossi and Hinrichs 2011). Local communities from ethanol-producing regions may show low levels of satisfaction regarding economic benefits or poverty reduction resulting from the presence of ethanol plants as well as concerns about traffic problems and risks of instability or decline of industry in the future (Hill et al. 2006; Selfa et al. 2011). In this regard, changes in and expansion of infrastructure related to ethanol projects also need the appraisal and acceptance of local communities in the context of Queensland as well as Australia. Overall, community engagement in decision-making relating to biofuel production projects enhances the awareness of both negative and positive aspects and thereby fostering implementation of more sustainable projects from social and environmental points of view.

Fuel ethanol producers are concerned about sustainability of increasing the area under cane production for the purpose of fuel ethanol production. This is because all productive land has been utilized, and hence further production can only occur on lands that are not as productive as the ones being used. The implication of this scenario is that the farmers have to use larger areas of land to obtain the same yield, if additional production is to occur on the land other than that being used at present due to lack of irrigation, lower rainfall, or the need to use less fertile soils (Akbar et al. 2018).

The area of land for growing sugarcane has gradually increased from 366,000 ha in 2007 to 377,000 ha in 2017. Likewise, the total production of sugarcane has increased from 34 million tons to 38 million tons. The land coverage for sugarcane production and harvesting is increasing and therefore offering a potential risk of disputes with land rights and land-use pattern (ASMC 2018). Conflicts in land rights happened in Thailand, one of the top sugar-producing countries in the world (Sawaengsak and Gheewala 2017). One of the main concerns about expanding sugarcane industry in Queensland, linked to the prominent role of industrial-scale plantations, is its effects on local land rights. Particularly, the indigenous people with traditional claims to land are likely to be disadvantaged by sugarcane farming expansion as formal recognition of their claims is limited in practice in Queensland. In Queensland, where 7% of Aboriginal people of total population live, local land rights is an important social issue.

To follow the mandate of the Queensland government regarding the use of biodiesel and bioethanol for transport, more land for sugarcane production would be needed. Other farmers, such as livestock and fishermen will be affected due to the expansion of land for sugarcane cultivation. In addition, the fishermen will be affected given the quality of water in the river in the catchment area and creeks might be deteriorated and therefore impact the fish stock. It can be clearly assumed that there will be both positive and negative social impacts of biofuel production from sugarcane (German et al. 2011; O'Hara 2011).

12.12 Economic Impacts

The gross value of production of sugarcane to the Queensland economy in 2013–2014 was $1.165 billion which represents about 10% of the total value of all agricultural production in Queensland. The sugar industry is therefore incredibly significant to Queensland and Australia's economy. The economic impacts of biofuel production include job creation or flow of labor force and income generation by farmers, income of laborers, and the overall impact at the regional and national levels. The cost of large-scale production of bio-based products is currently high in developed countries. For example, the production cost of biofuels may be three times higher than that of petroleum fuels, without, however, considering the nonmarket benefits. Conversely, in developing countries, the costs of producing biofuels are much lower than those in the OECD countries, including Australia which is very near to the world market price of petroleum fuel (United Nations 2008).

Importantly, economic advantages of a biofuel industry would include value added to the feedstock, an increased number of rural manufacturing jobs, an increased income tax, investments in plant and equipment, reduced greenhouse gas emissions, reduced reliance on crude oil imports, and supported agriculture by providing a new labor and market opportunities for domestic crops. In recent years, the importance of nonfood crops has increased significantly. The opportunity to grow nonfood crops under the compulsory set-aside scheme is an option to increase biofuel products (Roebeling et al. 2007).

A case study for Sarina ethanol generation and sugar production facility showed that the plant created 36 permanent jobs and 222 flow-on jobs, 389 construction direct jobs, and 256 flow-on jobs, adding $7.7 million to the household income in the region. However, caution is required in extending the results more broadly across regions, as these data do not take into account potential impacts on associated industries (Commonwealth Scientific and Industrial Research Organization [CSIRO] 2007). Nevertheless, it is important to underline the cost-effective and cooperative management strategies to preserve the livelihoods of thousands of cane farmers and the economic sustainability of their industry.

The major disadvantage of fuel ethanol, however, is its production cost. The production cost per liter of ethanol is still high compared to that per liter at current world crude oil prices for unleaded petrol. Consequently, the production of ethanol requires government assistance to be competitive even for larger producers. A study by the Australian Bureau of Agricultural and Resource Economics found that the production of ethanol is not commercially viable in Australia without government assistance for achieving the associated environmental and social benefits (Cochran et al. 2010).

12.13 Conclusion

Sugarcane production has been a significant activity in Queensland. This activity is being extended to Northern New South Wales and Western Australia, due to increased interest placed on the use of by-products of sugar production. As a consequence, the area under sugarcane cultivation is constantly expanding. This expansion includes both positive and negative environmental, social, and economic impacts. The positive impacts include increasing Australia's capacity to synthesize its own fuel with the view to reducing fuel imports and to providing cleaner environment (e.g., reduced emission and limited soil contamination). In addition, the expanded sugarcane cultivation will provide incentives to younger generation to not to move out of rural areas, thus ensuring long-term sustainability of sugarcane farming. The negative effects include nutrient leaching into the Great Barrier Reef (Coast protection), pollution of water in the GBR, impacts on native title, and reduction in the productive capacity of cane fields due to running-off of nutrients. To address the negative impacts, the Queensland government with the support of the Government of Australia has taken initiatives to minimize negative impacts and maximize the benefits of sugarcane farming. The federal and Queensland governments have introduced programs such as GBR Foundation Partnership (Department of Environment and Energy 2018b, Reef CRC, Queensland's Biofutures Program and Smartcane BMP (Queensland Government 2018). The Australian government has established the Reef Trust to improve water quality, restore coastal ecosystem health, and enhance species protection in the Great Barrier Reef World Heritage Area. The government has also established GBR foundation in 2000 in response to the UN World Heritage Convention to protect the GBR heritage site. The GBR Foundation partnership is the collaboration of Reef Trust and the GBR foundation administered by the Department of Environment and Energy. The ultimate aim of the GBR Foundation Partnership is to implement key actions and achieve key outcomes of the joint Australian Government Reef 2050 Plan (updated) which was released in July 2018. Hopefully, intensive programs that the federal and Queensland governments are introducing (GBR Foundation Partnership, Reef CRC, Queensland's Biofutures Program) will help find suitable solutions to minimizing the negative impacts of sugarcane cultivation for biofuel production and enhance its production and role as a biofuel source in the country.

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Chapter 13
Sugarcane Biofuel Production in Indonesia

Semida Silveira and Dilip Khatiwada

13.1 Introduction

Indonesia's energy system is largely fossil fuel-based (Ministry of Energy and Mineral Resources [MEMR] 2016). Indonesia became an importer of fossil oil after 2003 due to the declining domestic production and increasing oil consumption (BP Statistical Review of World Energy 2016). The country accounts for 35% of the total energy demand in Southeast Asia (International Energy Agency [IEA] 2017). The share of modern renewables is still limited. The contribution of biomass in the primary energy supply was 20% in 2015, but traditional biomass dominates in cooking and thermal services (MEMR 2016). Indonesia aims at reducing energy dependency and GHG emissions, as well as diversifying energy sources (Kumar et al. 2013; Mujiyanto and Tiess 2013).

Located in a tropical region, Indonesia is endowed with abundant biomass resources. There is significant consumption of traditional biomass in the residential sector, not least in the most remote areas. But there is understanding that modernization of biomass utilization can be a valuable strategy to meet increasing energy demand, create jobs, and reduce poverty (Yan and Lin 2009). In fact, the government of Indonesia sees bioenergy as an attractive option to promote socioeconomic development and improve energy security. Therefore, bioenergy is receiving increased attention in the country. A main preoccupation is to combine the local resource potential with competitive technological options to provide modern and reliable energy services and, at the same time, promote sustainable development. In addition, deforestation and land degradation are the main sources of GHG

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emissions in Indonesia and the primary cause for the loss of biodiversity and ecosystem services (Ramdani and Hino 2013; Susanti and Maryudi 2016; Uusitalo et al. 2014). Finding ways to reduce the degradation of forest resources and improve agriculture while also deploying bioenergy could have both environmental and social positive impacts.

The government has responded to energy security and climate challenges through legislation, targets and strategies for renewable energy, green growth, and natural resource management. A number of goals have been set, including an increase in renewable energy to 23% by 2025 (Bridle et al. 2018; Mujiyanto and Tiess 2013). Through its Nationally Determined Contribution (NDC), Indonesia has pledged to reduce emissions by 26% in relation to a business-as-usual scenario by 2020. Given that the transport sector poses particular energy security concerns, the government aims at raising biofuel use to 5% of the total national energy consumption by 2025 (Jupesta 2010; Hasan et al. 2012). These targets can be seen within the broader program of green growth, which aims at transforming energy and development pathways to achieve long-term sustainability.

Responding to concerns about the rapidly growing consumption of imported petroleum fuels, the government initiated a biofuel program in 2006 which included mandatory biofuel blending. Ambitious targets were set for biofuels: 30% biodiesel and 20% bioethanol by 2025 (Indonesia Regulation 12/2015) (Global Agriculture Information Network [GAIN] 2016, 2018). Unfortunately, due to the lack of biofuel production infrastructure, feedstock supply gaps, and stronger focus on palm oil and diesel, the bioethanol production in the country remains negligible (GAIN 2017a). Although agricultural crops and residues are currently utilized for liquid biofuel and bioelectricity generation in Indonesia, the adoption of biofuels has been slower than anticipated. Fuel ethanol for domestic blending effectively ended in 2010 due to economic and political reasons (GAIN 2015; Khatiwada and Silveira 2017).

This chapter addresses the conditions and potential for the development of first-generation sugarcane-based bioethanol industry in Indonesia. We consider feedstock and the industrial capacity for bioethanol production in the country in the context of present policies and transformations required to address increasing demand for transport fuels and climate change. Currently, only first-generation biofuels are produced at industrial scale in Indonesia, mostly palm oil-based biodiesel. Second-generation biofuels can be produced from a variety of biomass sources such as wood, residues, and waste, and the so-called third-generation biofuels can be derived from algae. These options shall be explored in the future as the country develops an integrated strategy for bioenergy. For the time being, Indonesia is still to capitalize on opportunities derived from efficiency improvements in the sugarcane agro-industry, which is the first step in building a robust solid biofuel industry. Therefore, the focus of this chapter is on this first step.

13.2 Land and Sugarcane for Sugar and Bioethanol Production

Indonesia has a long history as sugar producer and is one of the top 10 sugarcane producers in the world. The country was self-sufficient until 1985, as reported by the Indonesian Sugar Cane Statistics (Badan Pusat Statistik [BPS] 2013). Sugarcane crop plantations cover 445 thousand hectares mainly in Java (60.3%) and Sumatra (36.7%) (Ministry of Agriculture [MoA] 2018). Java's sugarcane mills have contributed 63% of the Indonesian white sugar production in 2015/2016 (GAIN 2017b). Opportunities exist for expansion of sugarcane plantations in response to national policies and growing global markets for biofuels. However, the majority of the sugarcane cultivation is done by smallholders in Java (MoA 2018). Thus, any program for performance improvement needs to consider ways to build upon the existing structure, so as to empower and benefit multiple small producers.

Figure 13.1 shows the evolution of sugarcane yields (tonne ha^{-1}) and sugarcane plantation areas (in Mha) in Indonesia between 1990 and 2016. Notably, yields have fluctuated significantly, while the total sugarcane area has not varied as much in the last few decades. Lack of modernization of sugarcane systems, including cultivation practices and industrial operations, along with increasing competition are the main reasons for decreased performance of sugarcane-based agro-industry (Khatiwada and Silveira 2017).

Indonesia plans to achieve sugar self-sufficiency by 2020 and, at the same time, has defined mandatory bioethanol targets. Despite the national demand around 5.93 million tonnes sugar, only around two million tons are presently being produced

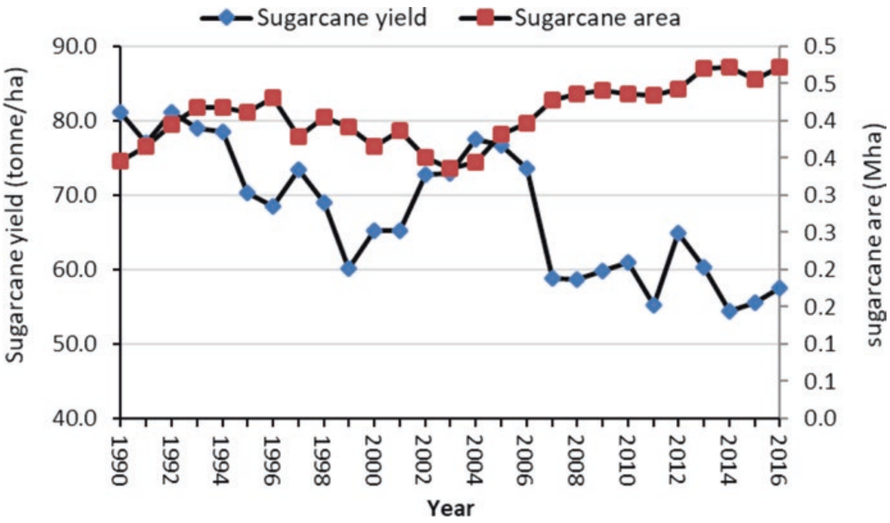

Fig. 13.1 Sugarcane-planted areas and yields in Indonesia (1990–2016). (Source: Food and Agriculture Organization of the United Nations (FAOSTAT 2018))

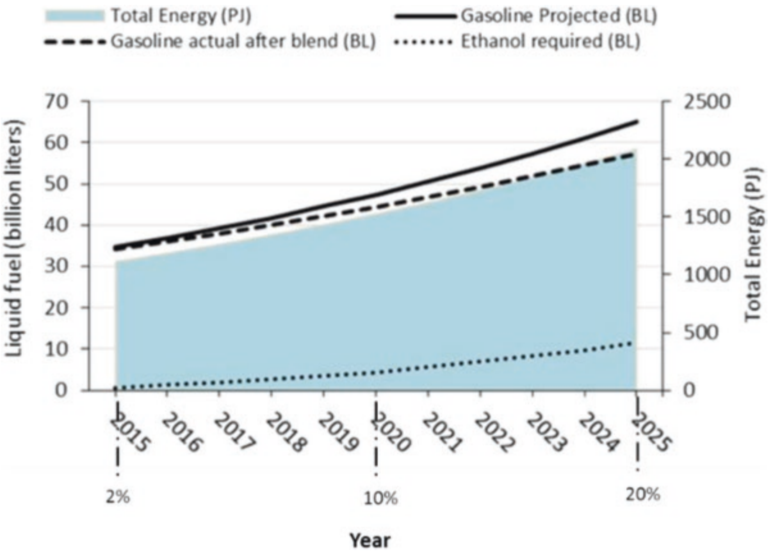

Fig. 13.2 Gasoline and bioethanol projection as per transport energy demand and blend mandates. (Source: Khatiwada and Silveira 2017). (Note: The projection is based on the historic trend and energy equivalent using linear regression analysis (interpolation and extrapolation). The primary Y-axis represents gasoline projection (with and without bioethanol blend) and ethanol requirement for mandatory blend, while the secondary Y-axis gives total energy consumption in the transport sector in Indonesia)

nationally (GAIN 2017b). Approximately 40 mills (out of the total 63 mills) are over 100 years old. The sugar price is regulated in the country, which compromises the competitiveness of the sugar industry and hampers production expansion.

As mentioned previously, Indonesia has a bioethanol blending mandate for the transportation sector. Figure 13.2 shows the projections for gasoline and bioethanol for meeting the blending mandate until 2025. The main potential feedstocks for bioethanol in the country are sugarcane and cassava. However, sugarcane has the greatest potential considering factors such as (i) food crop with surplus production, (ii) plant productivity, (iii) potential biofuel yield, (iv) plant development readiness, (vi) government policies in place, and (vii) possibility to expand plantations in marginal land (Hambali et al. 2016).

Sugarcane-based production systems comprise the production of sugar and coproducts, i.e., molasses and bagasse (Khatiwada and Silveira 2009). The sugarcane stalk is crushed in sugarcane mills, leaving the bagasse as residue. Sugar juice passes through multiple crystallization phases during which crystal white sugar is produced. When no more sugar can be recovered, there is still a residual syrup, molasses, a low-value coproduct that can be used for the production of fuel ethanol. Sugarcane juice can be diverted for the production of bioethanol, particularly when there is surplus sugarcane feedstock left after the sugar production. Bagasse is combusted in boilers to provide the energy (i.e., steam and electricity) requirements of the plant. The anhydrous ethanol used as the gasoline blend is obtained in the sugarcane biorefinery, following the process of fermentation, distillation, and dehydration of molasses or juice (in the case of surplus sugar). Sugarcane biomass (excess bagasse and residues) can be used for generating bioelectricity in efficient cogeneration plants (Khatiwada et al. 2012, 2016; Khatiwada and Silveira 2017).

Indonesia produced 27.2 million tonnes (Mtonnes) of sugarcane on 0.47 million hectares (Mha) of land in 2016 (FAOSTAT 2018). Thus, less than 1% of the total agricultural land was used for sugarcane. Currently, sugarcane juice is mainly used to produce sugar for domestic consumption, while molasses are readily available for bioethanol production. Khatiwada and Silveira (2017) made projections to verify whether the sugarcane feedstock can meet the national demand for both sugar and bioethanol. The projections considered the fact that Indonesia aims at becoming self-sufficient in sugar production; thus, the focus was on molasses-based bioethanol as a first step. When sugar demand is met, surplus cane juice is diverted for bioethanol production. The projections rely on land availability for sugarcane plantations estimated by Winrock International (i.e., 5 Mha) (Khatiwada and Silveira 2017; Winrock International 2009).

Table 13.1 shows the projections for sugar, sugarcane, and molasses production until 2025, indicating the amount of land required for meeting self-sufficiency in sugar and the molasses derived from the process. Doubling the planted area from 2015 is necessary to achieve sugar self-sufficiency in 2020.

Table 13.2 shows the projections for gasoline demand and the amount of bioethanol needed to meet the blending targets set by the Indonesian government.

Table 13.1 Projection of sugar, sugarcane, and molasses production to meet sugar self-sufficiency in Indonesia by 2020

Year	Sugar demand[a] (Mtonne)	Sugarcane production (Mtonne)[b]			Molasses production (Mtonne)	Total sugarcane area (Mha)
		From existing land	For meeting sugar self-sufficiency by 2020	Total sugarcane		
2015	3.01	37.6	0.00	37.60	1.80	0.47
2016	3.77	37.6	9.55	47.15	2.26	0.59
2017	4.54	37.6	19.10	56.70	2.72	0.71
2018	5.30	37.6	28.65	66.25	3.18	0.83
2019	6.06	37.6	38.19	75.79	3.64	0.95
2020	**6.83**	**37.6**	**47.74**	**85.34**	**4.10**	**1.07**
2021	6.92	37.6	48.89	86.49	4.15	1.08
2022	7.01	37.6	50.05	87.65	4.21	1.10
2023	7.11	37.6	51.22	88.82	4.26	1.11
2024	7.20	37.6	52.41	90.01	4.32	1.13
2025	7.30	37.6	53.62	91.22	4.38	1.14

Source: Khatiwada and Silveira (2017)

[a] Population was 248.8 million in 2013. We consider an annual population growth rate of 1.34%

[b] Cane yield of 80 tonne ha^{-1} is considered; sugar self-sufficiency is expected by 2020

Table 13.2 Total gasoline and equivalent energy projection for meeting the blending targets in Indonesia

Year	Total gasoline projection (BL)[a]	Total energy equivalent (PJ)[b]	Gasoline demand after blend (BL)[c]	Ethanol blend[d] (% of gasoline)	Ethanol required (BL)
2015	**34.6**	**1113.9**	**34.2**	**2.0%**	**0.68**
2016	36.9	1186.3	36.0	3.6%	1.30
2017	39.2	1263.4	37.9	5.2%	1.97
2018	41.8	1345.5	40.0	6.8%	2.72
2019	44.5	1433.0	42.2	8.4%	3.54
2020	**47.4**	**1526.1**	**44.5**	**10.0%**	**4.45**
2021	50.5	1625.3	46.8	12.0%	5.62
2022	53.8	1730.9	49.2	14.0%	6.89
2023	57.3	1843.5	51.8	16.0%	8.29
2024	61.0	1963.3	54.5	18.0%	9.82
2025	**64.9**	**2090.9**	**57.4**	**20.0%**	**11.48**

Source: Khatiwada and Silveira (2017)
Average annual energy growth rate is assumed to be 6.5% in the transport sector

In spite of the government's plans, sugar production has dropped lately due to El Nino in 2015/2016 (GAIN 2017b). Climate change may also pose threats to sugarcane in Indonesia due to increasing average temperature, a key factor in the sugarcane ripening process (de Almeida Silva and Caputo 2012). Higher average temperature is likely to affect the sugar content negatively. There is, therefore, need to consider adaptation methods for addressing the impacts of changing temperatures.

13.3 Scenarios for Meeting Sugar Self-Sufficiency and Ethanol Blending Mandates

The blending mandates for ethanol aim at a 10% target by 2020 and 20% by 2025. However, there is currently no road map defining how the bioethanol blending targets will be achieved in the transport sector. Bioethanol producers have installed molasses-based plants with a capacity for 339 million liters in 2010. Surprisingly, both production and use of ethanol have come to a halt since then, due to lack of economic competitiveness in the sugarcane agro-industrial sector, decreasing yields, and volatile international prices for petroleum.

Khatiwada and Silveira (2017) developed scenarios to investigate conditions for sugarcane-based bioethanol production in Indonesia and for meeting bioethanol blending targets and sugar self-sufficiency. The parameters considered in four different scenarios are summarized in Table 13.3. The scenarios consider (a) land use with low-medium-high cane yields, (b) meeting sugar self-sufficiency by 2020, (c) meeting bioethanol mandates, and (d) use of available land for sugarcane production. The study shows that if surplus sugarcane juice and sugarcane

Table 13.3 Scenarios for meeting bioethanol blending mandate, also considering sugar self-sufficiency and utilization of identified land suitable for sugarcane

						Ethanol production			Scenario description
	Cane yield	Sugar recovery	Sugarcane area[c]	Sugar self-sufficiency[c]		From molasses	From cane juice	Total potential[c]	
Scenarios[a, b]	tonne/ha	(%)	Mha	yes/no	year	Billion liters (BL)			
Sc-1: Current sugarcane fields	58-70-80 (low-BAU-high)	7.76	0.47	no	–	yes	–	(?)	Sugarcane yield: low, reference, and high (58-70-80) tonne/ha; sugar recovery· 7.76%; current sugarcane land 0.47 Mha; molasses ethanol; sugar-deficit condition
Sc-2: Reaching sugar self-sufficiency	80	8.00	(?)	yes	2020	yes	–	(?)	Sugarcane high yield (80 tonne/ha); sugar self-sufficiency[7] from 2020 as per the new government regulation) and beyond as per the projected sugar demand (25 kg sugar/capita and 1.34% population growth); molasses ethanol; linear regression for sugar demand
Sc-3: Meeting bioethanol mandate	80	8.00	(?)	yes	(?)	yes	yes	(?)	Sugarcane high yield (80 tonne/ha); projected sugar demand (25 kg sugar/capita and 1.34% population growth); molasses and juice ethanol; linear regression for bioethanol blend and sugar demand
Sc-4: Expansion of sugarcane fields	80	8.00	0.47–547	yes	(?)	yes	yes	(?)	Sugarcane high yield (80 tonne/ha); sugar self-sufficiency as per the projected demand (25 kg sugar/capita and 1.34% population growth) and land availability; molasses and juice ethanol; linear regression for bioethanol blend mandate, sugar demand, and land use

Source: Khatiwada and Silveira (2017)

[a] Bioethanol blend mandates (% of gasoline consumption) are 2% (2015), 10% (2020) and 20% (2025) as per the new government regulation (Regulation 20/2014 and 12/2015) for non-subsidized gasoline fuel

[b] As per the government new policy sugar-sufficiency is met in 2019/2020

[c] Bioethanol potential (Sc-1 to Sc-4), sugarcane area (Sc-2 and 3), and sugar self-sufficiency level (Sc-3 and 4) are to be found as pointed by (?) symbol

by-products (e.g., molasses and bagasse) are used for energy production, there is no need for bioethanol and food production to outcompete each other.

However, scenarios (Sc-1 and Sc-2) showed that it would not be possible to meet the stipulated bioethanol blending targets using only molasses, even if plantations are expanded for meeting the domestic sugar demand by 2020. Scenario 3 (Sc-3) examined under what conditions bioethanol mandates can be achieved by 2015, 2020, and 2025. For this, it is necessary to expand sugarcane plantations and also use cane juice for bioethanol production. In order to meet the bioethanol blending target of 10% by 2020, 1.6 Mha sugarcane fields are required; 1.07 Mha is sufficient to produce the sugarcane required for sugar production. This allows diverting the surplus sugar juice for bioethanol production. We need a total land area of 2.76 Mha for meeting both the domestic sugar demand and the bioethanol mandate of 20% blend by 2025. The total ethanol required for 20% blend in the transport sector in Indonesia is 11.48 billion liters (BL). We assume the estimation of available land proposed by Winrock International (Winrock International 2009) (i.e., 5 Mha) which is based on a digitalized geographical information system and excludes peat land, forest, and sensitive areas for sugarcane field expansion.

Figure 13.3 shows the land requirements, molasses-bioethanol production potential, and projected bioethanol demand to meet the national bioethanol targets during the period between 2015 and 2025 in Indonesia. Sugarcane plantation areas of 1.60 Mha and 2.76 Mha are required for meeting the dual objectives of sugar self-sufficiency and bioethanol mandates by 2020 and 2025, respectively. Juice ethanol is required to meet the blending targets set for 2020 (i.e., 4.45 BL ethanol) and 2025 (i.e., 11.48 BL ethanol). Moreover, as shown in Fig. 13.4, it is possible to go beyond

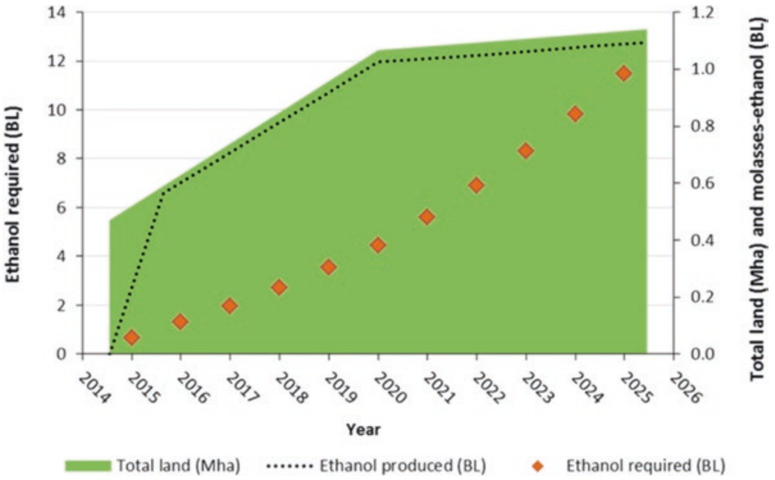

Fig. 13.3 Total land required (million hectares, Mha) for meeting sugar self-sufficiency and molasses ethanol production potential in billion liters (BL). (Source: Khatiwada and Silveira 2017). (Note: Ethanol required volume (BL) to meet the mandate is in primary Y-axis; total land (Mha) and ethanol produced (BL) are presented in the secondary Y-axis)

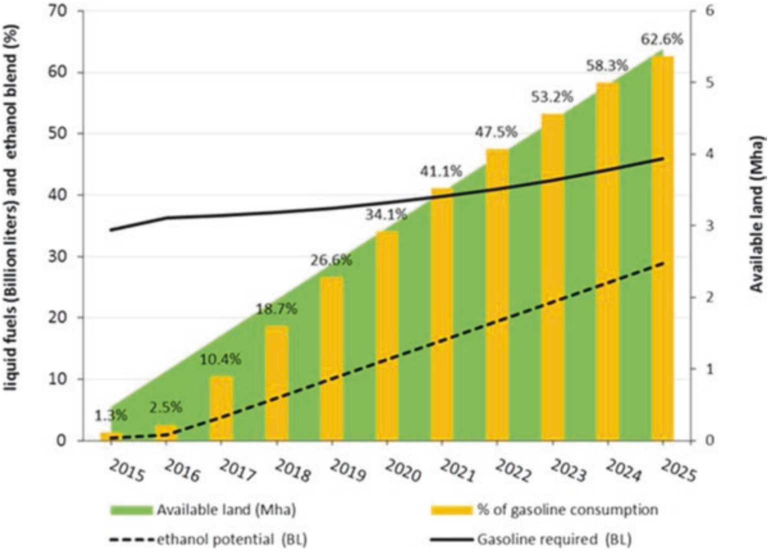

Fig. 13.4 Percentage of gasoline substitution in the transport sector in Indonesia when sugarcane is produced from available land (without compromising sugar demand). (Source: Khatiwada and Silveira 2017). (Note: Primary Y-axis shows bioethanol potential, gasoline demand, and % of gasoline substitution; secondary Y-axis represents the corresponding sugarcane field)

present bioethanol targets even if we remain limited to the first-generation bioethanol production. Thus, 34% of the bioethanol blend mandate by 2020 and 63% by 2025 could be achieved when available land is used for sugarcane cultivation, and sugar juice is diverted for fuel ethanol production after meeting the domestic sugar demand in Indonesia.

13.4 Potential Energy and Climate Gains from Sugarcane Bioethanol Production and Fuel Substitution

How much energy is required to produce bioethanol, and what climate benefits can be accrued from substituting gasoline with bioethanol? Certainly, this depends on many factors, including the type and origin of the feedstock used and technology applied in the bioethanol production, among other factors. In case of bioethanol from sugarcane in Indonesia, a first step would be to use molasses for bioethanol production and then move forward to use also cane juice and later introduce second-generation technologies. Here, we will scrutinize the benefits from bioethanol produced from molasses in the context of Indonesia.

It is crucial to estimate the energy required during the life cycle of sugarcane molasses conversion to ethanol to make sure that there are resource gains along the production and use chain. In addition, it is important to understand the effects of the

Table 13.4 Life cycle energy consumption for bioethanol production from molasses in Indonesia

Process	Fossil inputs (MJ l^{-1})	Renewable energy inputs (MJ l^{-1})
Cane cultivation		
Fertilizer and herbicide production	0.63	
Sugarcane seeds production	0.01	
Human labor	0.50	0.10
Cane milling		
Grid electricity consumption	0.05	
Coal consumption	0.69	
Bagasse consumption		10.03
Ethanol production		
Grid electricity use	1.00	
Fuel combustion		14.57
Transportation		
Cane	0.26	
Filter cake	0.04	
Stillage	0.06	
Molasses	0.01	
Ethanol	0.23	
Total	**3.49**	**24.69**
NEV	**−6.99**	
NREV	**17.71**	
ER	**6.07**	

Source: Khatiwada et al. (2016)
Note: Net energy value (NEV), net renewable energy value (NREV), and energy ratio (ER). ER is the ratio of LHV (lower heating value) of ethanol to the fossil energy required to produce it

sugarcane-based agro-industry on climate change (i.e., in terms of greenhouse gas emissions). Therefore, a cradle-to-grave life cycle analysis of the sugarcane-molasses to biofuel pathway was carried out. The resource consumption and climate change impacts measured in terms of energy utilization (including fossil and biomass) and GHG emissions go from feedstock cultivation to bioethanol production and use, and include also transport, processing, and conversion features. The material and energy inputs in the form of fertilizers, chemicals, electricity, and corresponding environmental impacts are also considered. Thus, to estimate the life cycle emissions and energy consumption along the whole production chain, energy, material, and emission flows were included in the analysis in the form of energy consumption during the fuel production and energy and GHG emissions during the production and use of the fuel.

Table 13.4 provides the resource or energy consumption for the production of sugarcane molasses bioethanol. The total energy consumption is 28.18 MJ (fossil: 3.49 MJ and renewable: 24.69 MJ) per liter of ethanol produced. In the total energy consumption, cane milling (38%) and ethanol production (55%) consume most of the energy. In terms of fossil fuel consumption, the amount of nonrenewable energy

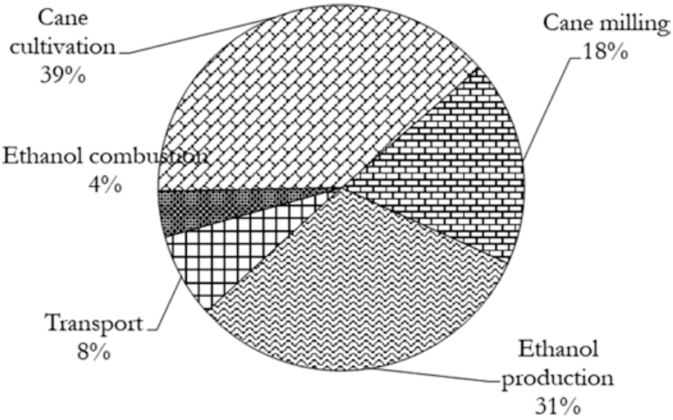

Fig. 13.5 Net greenhouse gas emissions of ethanol production in Indonesia. (Source: Khatiwada et al. 2016)

required for the production of nitrogen fertilizers (cane cultivation) and coal use in cane milling and ethanol production is high compared to other activities.

The value of ER is highly sensitive to changes in cane yield. Improvements in agricultural practices will improve cane yield, thus leading to higher energy ratio (ER). This is definitely one issue that deserves attention. An efficient cogeneration system with the use of high pressure/temperature boilers and turbines/generators can improve the energy output. In this way, not only the internal energy demand is met in the sugarcane mills but surplus bioelectricity can be produced. The efficient cogeneration plant can produce 100–150 kWh of surplus electricity per tonne of cane processed using sugarcane biomass (bagasse and trash) (Khatiwada et al. 2012).

Considering the environmental impact or GHG emissions from sugarcane farming/cultivation and cane transport, 53.2 kg of carbon dioxide equivalent (kgCO_{2eq}) per tonne cane (tc) or 4158 kgCO_{2eq} is produced per hectare (ha) of sugarcane area. If we consider the resource consumption or energy inputs, 24.1 GJ (of which 22.5 GJ are nonrenewable and 1.6 GJ are renewable) are consumed per hectare (ha) during the sugarcane cultivation and harvesting phases.

The environmental impact of converting sugarcane molasses to bioethanol was analyzed based on the emissions during the complete life cycle chain. The cane cultivation leads to 49 kgCO_{2eq} per tonne cane (tc) harvested, N_2O emissions being the major contributor. This is followed by cane trash burning and decomposition. The transport of cane and filter cake emits 4.9 kgCO_{2eq} tc^{-1}. Life cycle emissions from sugarcane bioethanol production are estimated at 29.1 gCO_{2eq} MJ^{-1} of bioethanol, leading to a 67% emission reduction compared to gasoline. The cane cultivation phase contributes most to the total emissions (Fig. 13.5). The major contribution within the cultivation phase is the production and application of nitrogen fertilizers.

Besides sugar and bioethanol production in sugarcane mills, there is significant potential to produce bioelectricity when sugarcane biomass (bagasse and trash/

Table 13.5 Surplus bioelectricity production potential in Indonesia in different conditions and time frame

Particulars[a]	Existing land condition (2015)[b]	Sugar self-sufficiency (2020)[c]	Bioethanol mandates		
			2% blend (2015)	10% blend (2020)	20% blend (2025)
Sugarcane production (Mtonne)	32.9	85.3	56.9	128.1	221.0
Bioelectricity potential (TWh)	4.94	12.80	8.54	19.22	33.16
Biopower (MW)	563.36	1461.35	974.71	2194.25	3784.87

Source: Khatiwada and Silveira (2017)

[a] Surplus electricity of 150 kWh t^{-1} cane is considered

[b] Existing land of 0.47 Mha produces 33 Mtonne sugarcane in Indonesia

[c] It is assumed that sugar self-sufficiency would be achieved by 2020

residues) is efficiently used in combined heat and power plants. With efficient cogeneration, 100–150 kWh $tonne^{-1}$ surplus power can be generated after meeting the internal energy requirements in sugarcane mills (Khatiwada et al. 2012). The Indonesian power sector is dominated by coal and natural gas (MEMR 2016). Thus, the use of sugarcane biomass (bagasse and trash) from sugar ethanol production can contribute to improving the total energy and cost balance of the industry, while also generating renewable electricity to the grid.

Table 13.5 shows the bioelectricity potential considering sugar self-sufficiency and bioethanol mandates. Our estimations show that, at present conditions, if efficient CHP plants are used, 563MW (i.e., 4.94 TWh) can be produced and connected to the grid in Indonesia. Surplus bioelectricity would amount to 12.8 TWh (i.e., 1461 MW) if the sugarcane biomass (i.e., bagasse and trash) obtained after meeting the sugar self-sufficiency in Indonesia in 2020 is used for electricity generation.

Similarly, sugarcane bioenergy can produce 8.54 TWh, 19.22 TWh, and 33.16 TWh as sugarcane bagasse and residues are used after meeting the bioethanol blending targets in 2015, 2020, and 2025, respectively. Total electricity sales were 187.5 TWh in 2013 in Indonesia. Under present conditions, the share of bioelectricity in the national electricity mix would be around 3%. Sugarcane biomass can produce around 6.5% of bioelectricity when sugar self-sufficiency is met in 2020, considering the projected electricity consumption for the same year.

Bioelectricity is carbon-neutral when sustainability requirements are met, and it can replace carbon-intensive coal electricity in Indonesia. In fact, bioelectricity has become a complementary option to hydropower in other sugarcane-producing countries such as Brazil and Nepal (Khatiwada et al. 2012). However, there are presently no studies on the regulatory frameworks and institutional arrangements required for promoting bioelectricity in Indonesia. There is an urgent need to explore the bioelectricity potential as part of concerted actions to promote biofuels and renewable energy at large as well as part of strategies to improve energy access and achieve the SDGs (Sustainable Development Goals) (International Renewable Energy Agency [IRENA] – International Energy Agency [IEA] 2017)

13.5 Conditions for Developing the Sugar-Bioethanol Potential in Indonesia

Indonesia is largely dependent on fossil fuels, including oil, coal, and natural gas, and is on a nonsustainable track when it comes to its energy matrix. Despite large renewable sources, only a small portion of the energy demand in the country is met with renewables. It is, therefore, imperative to change the current patterns of energy consumption to put the country on a sustainable track. Increased ability to deploy modern bioenergy can potentially contribute to positive impacts such as improved energy security, welfare, and capacity to meet greenhouse gas (GHG) mitigation commitments.

Opportunities exist to develop a sustainable sugar-bioethanol industry based on sugarcane in Indonesia. Although the country has been a producer of sugar and bioethanol, and has put in place policies to promote biofuels in transport and renewable energy at large, there is still much to be done to set the sugar-bioethanol industry on track toward a modern and efficient industry. Reasons for the slow transformation of the industry can be found in various bottlenecks and policy incoherence and lack of interplay between local practices and national agendas for energy, climate, and development.

Most sugarcane mills operating in Indonesia are old, and 65% of them have been operating for more than 100 years. Old cultivation practices and industrial operations, along with increasing competition, are the main reasons for reduced performance of the sugarcane agro-industries in the past years. It is important to explore development toward a bio-based economy, with integrated resource utilization for harnesing the full potential of bioresources in Indonesia. Meanwhile, opportunities are being lost to pursue sugar self-sufficiency and bioethanol production for meeting the country's mandatory blending targets.

Modernization of sugarcane systems are much needed for the country to capitalize on the opportunities in this sector. The production of bioethanol from bagasse is a "low-hanging fruit." But to fully explore the modernization potential, strategies and incentives need to be put in place at various stages of the production and use chain. Improvements in agricultural management practices as well as supply-chain logistics are necessary for improving energy efficiency and sugarcane yields. The productivity gains accrued from the modernization of agricultural and production systems will benefit both food and fuel production, whereas bioelectricity generated from the sugar-ethanol industries can help to diversify energy sources and improve the competitiveness of the sector. Renewable bioelectricity from sugarcane biomass provides an attractive way to reduce fossil fuel energy dependency and reduce emissions, while also promoting the sustainable development.

Clearly, the area planted will have to be expanded as population and the demand for sugar increases. The amount of molasses increases together with sugar production, thus offering an opportunity to also expand the production of bioethanol. However, the use of juice will be needed if the blending targets are to be met with national bioethanol production for 2020 (i.e., 4.45 BL ethanol) and 2025 (i.e., 11.48 BL ethanol). This translates into sugarcane feedstock obtained from 1.60 Mha and 2.76 Mha land, respectively. It is possible to go beyond the present bioethanol targets even if we remain limited to the first-generation bioethanol production. Measures of 34% of bioethanol blend mandate by 2020 and 63% by 2025 could be achieved when available land is used for sugarcane cultivation, and sugar juice is diverted for fuel ethanol production after meeting the domestic sugar demand in Indonesia. Sustainable bioenergy production from degraded land can reduce the potential conflict with other food crops.

Today, the availability of sugarcane molasses as a bioethanol feedstock is closely tied to the demand for crystalline sugar in the household and commercial sectors. While molasses offer a first step to boost bioethanol production, achieving the blending targets ultimately requires higher agricultural productivity and/or wider availability of agricultural residues to facilitate the coproduction of biofuels and electricity.

The difficulty in achieving the blending targets for fuel ethanol arises from a number of factors, including policy uncertainty, opportunity costs for production and use of molasses, and structural problems in the sugar and bioethanol sectors. The bioethanol price remains higher than gasoline, despite the price regulation for bioethanol. Thus, bioethanol cannot compete with gasoline. In fact, the stakeholders indicate that the market price is at a deadlock. As a result, producers of bioethanol are more prone to selling their product to smaller industries for purposes other than fuel (e.g., cosmetic and pharmaceutical industries). This market is limited and does not offer enough incentive for production expansion.

In the mid-term, bioenergy deployment may focus on the conversion of biomass into marketable bioproducts and energy. This can be done using biorefineries for multiple products and services (e.g., liquid biofuels, biogas, bioelectricity, feed) with current available commercial technologies. Meanwhile, a more complex system using different feedstocks and conversion technologies can be explored and integrated over time. In the long-term, Indonesia should consider the incorporation of second-generation bioenergy to improve resource efficiency and reduce emissions, as well as delink the expansion of bioenergy production from the expansion of energy crops.

The bioenergy potential has been clearly recognized in Indonesia. Still, efforts need to be intensified in terms of policy adjustments, incentives, and coordinated actions around a strategy to guarantee a sustainable transition from traditional practices to modern and sustainable solutions. A holistic approach is required to improve competitiveness on both the agricultural and industrial sides, leading to enhanced energy service provision and improved self-sufficiency. The synergies between agricultural and industrial sectors are key to success in face of competing uses for land and water, the need for improved resource efficiency, and efforts to guarantee both food and fuel supply. The global climate benefits provide further incentive for Indonesia to explore its bioenergy potential. Linking bioenergy markets and ecosystem services to provide energy services, improve energy security, and promote sustainable livelihoods should be pursued as mutually reinforcing objectives to promote the sustainable development goals (SDGs) in Indonesia.

13.6 Conclusions

Sugar production for self-sufficiency and ethanol for meeting mandatory blending targets can be met from sugarcane feedstock using sustainable lands in Indonesia. Additional land areas of 1.60 Mha and 2.76 Mha are required for meeting the dual objectives by 2020 and 2025, respectively. Besides, there is an enormous potential to produce bioelectricity derived from sugarcane residues (trash and bagasse). The life cycle GHG emissions in the production and use of sugarcane-molasses bioethanol is 29 gCO_{2eq} per MJ which is 67% less in comparison to gasoline emissions. The energy yield ratio is 6.1, that is, fossil energy consumption is quite low in comparison to final energy content of bioethanol. Finally, in order to harness the potential of sugarcane biofuels in Indonesia, integrated and holistic implementation plans are required, including modernization of sugarcane mills, investments for biorefineries, and adjustment in policy frameworks to guarantee a transition toward sustainble solutions.

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Chapter 14
Sugarcane Biofuel Production in the USA

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Abbreviations

CHP	Combined heat and power
DOE	Department of Energy
DNR	Department of Natural Resources
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERS	Economic Research Service
RFS	Renewable Fuel Standard
RIN	Renewable identification number
UN	United Nations
US	United States
USA	United States of America
USDA	United States Department of Agriculture

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14.1 Overview of the Sugarcane Industry in the USA

14.1.1 Status of Sugarcane Production

Sugarcane has been extensively cultivated and processed in the USA since Etienne DeBoré first granulated sugar for commercial production in the state of Louisiana in 1795 (Heitmann 1987). In addition to Louisiana, sugarcane is grown in the mainland states of Florida and Texas. With the closure of the last sugar factory in 2017, the Pacific Ocean island state of Hawaii no longer cultivates the crop. In 2017–2018, sugarcane was harvested from ~345,000 hectares and processed in 16 raw sugar factories. Raw sugar was processed into white sugar in eight refineries.

Table 14.1 contains a comparison of production statistics among the states which cultivated sugarcane in the 2017–2018 production period. Biomass productivity varies considerably among the three mainland states. Averaged over the three most recent production years, sugarcane biomass yield in Mg ha^{-1} $year^{-1}$ is 92.4 for Florida, 78.5 for Texas, and 67.0 for Louisiana (USDA 2017). Lower comparative biomass yields for Louisiana and Texas reflect a short growing season in a temperate environment and semiarid conditions, respectively. Sugar recovery rate also varies, with Florida, Louisiana, and Texas averaging 12.13, 11.61, and 9.99%, respectively, as an average of production years from 1980 to 2017 (ERS USDA 2018a). Sugarcane accounts for approximately 45 percent of the total domestic sugar production, with sugar beets accounting for the rest (ERS USDA 2018b).

To ensure and protect the domestic supply of sugar and provide price stability, the USA uses price supports, domestic marketing allotments, and import quotas to control the supply of sugar marketed in the country (ERS USDA 2018c). The federal commodity support program features nonrecourse loans to processors and is designed to avoid the forfeiture of sugar put under loan in compliance with a no-cost provision for the federal government. Also designed to help avoid loan forfeitures is a provision that diverts excess sugar to conventional ethanol production.

14.1.2 Status of Energy Cane Production

Energy canes are complex hybrids between *Saccharum officinarum* L. and *S. spontaneum* L., *S. barberi* Jeswiet, and/or *S. sinense* Roxs. (Bischoff et al. 2008). Energy cane was developed as a biomass feedstock in response to higher fossil fuel prices

Table 14.1 US factory production statistics for the 2017–2018 production year

State	Metric tons of cane processed	Metric tons of 96° sugar produced	Cubic meters of molasses 79.5/80° Brix
Florida	15,688,470	1,760,447	367,400
Louisiana	13,639,452	1,649,335	294,643
Texas	1,493,041	149,794	41,325

Sugar J (2018a, b)

in the 1970s and the prediction by some that oil production had reached its peak. To determine geographic adaptation, energy cane performance trials were established to determine the biomass yield potential at multiple locations as far north as 33° North latitude (Owens et al. 2016). Dry matter yields ranged from 22 to 24 Mg ha^{-1} $year^{-1}$ at the most northerly site, where hybrids were challenged by cold temperatures, to over 45 Mg ha^{-1} $year^{-1}$ at the southern sites. Energy cane produces abundant biomass with relatively modest inputs, which makes a suitable feedstock for lignocellulosic conversion.

14.2 Bioenergy Production

14.2.1 Introduction

Fossil fuels have boosted industrialization and economic growth over the years. However, the adverse effects (greenhouse gas emission, air pollution, and global climate change) associated with fossil fuels have raised concerns regarding their economic and environmental sustainability and have shifted the attention to renewable energy sources such as wind, solar, nuclear, and bioenergy (Maradin et al. 2017). Bioenergy can be divided into first-generation crops such as sugars from sugarcane or sugar beets and starch from corn, rice, and wheat and second-generation energy sources such as various lignocellulosic biomass materials (Aita and Kim 2011). First-generation ethanol produced from crops has been the driving force in renewable energies. However, over the last decade, research on second-generation ethanol from lignocellulosic biomass has been searching for a significant breakthrough that will lead to it being cost competitive with first-generation ethanol. Unfortunately, the development of a lignocellulosic ethanol market has been slower than expected due to the perception of high technological risk, intensive capital costs, and the low oil prices that result in poor economics for the biorefineries (Kim and Kim 2014; Stephen et al. 2012).

14.2.2 First-Generation Biofuel Production

Sucrose, in the form of either raw sugar or molasses, is quite energy-rich with a combustion enthalpy of 16 MJ kg^{-1}; however, as carbohydrate it is non-suitable for direct energy conversion, especially through combustion. The most commonly proposed transformation is the microbial conversion to alcohols. Chemical conversion is possible but requires high-purity materials, typically at the level of refined sugar or above. For both microbial and chemical methods, the main challenge is the effective conversion and retention of the carbon.

From 1985 to 1987 several raw sugar/syrup/molasses-to-ethanol facilities have operated (up to 121,000 m^3 $year^{-1}$) and/or were planned (up to 586,000 m^3 $year^{-1}$) in Louisiana due to generous subsidies from the state of Louisiana. These subsidies ceased in 1989 and forced the existing facilities into bankruptcy or relocation to other states with subsidized corn-based ethanol (DNR Louisiana 2018; Troy 1993, 1994). The favorable regulatory environment created by the Energy Independence and Security Act of 2007 led to renewed efforts to produce sugarcane-based ethanol in the USA in Louisiana, California, and Hawaii (Jensen 2011; Voegele 2009). These projects were projected to generate an aggregate total of 375,000 m^3 $year^{-1}$ of ethanol, but none has achieved online status in the face of low fossil fuel prices. As of 2018, no large-scale fermentation-based fuel production from sugarcane or energy cane or molasses exists in Louisiana, Florida, Texas, or Hawaii (EIA 2018a). The economics are fundamentally challenged by the stoichiometry of the conversion. Five conversions of glucose/fructose are considered in Table 14.2.

The pyrolytic conversion of glucose to carbon, the conversion into syngas, and reforming the syngas to methane allow access to practically all chemicals derived from natural gas or coal. Also shown are the microbial conversion into ethanol and butanol, respectively. By assuming a stoichiometric yield (which cannot be achieved in an industrial facility), Table 14.2 shows the potential yield of the respective chemical and its market value. In the last column, the equivalent sugar price is given, i.e., if sugar would be below this value, cost parity between raw material and final product would be given (omitting any process cost, overhead, etc.).

Currently, the raw sugar price centers on 0.55 $ kg^{-1}, i.e., none of the described fuels can be made economically from cane sugar (even less from energy cane due to its lower sugar content). Blackstrap molasses are fairly expensive in the US at 132 $ t^{-1} due to their use as animal feed (Feedstuff 2018; USDA 2018b). Considering the average composition of Louisiana blackstrap molasses, the sugars (sucrose and invert) would cost $0.304 kg^{-1}, a feedstock cost that would prohibit its use for fuel production except for butanol. However, butanol's value exceeds gasoline prices in the USA, and it is therefore predominantly used as a solvent and a chemical intermediate. While there have been many studies detailing the

Table 14.2 Basic sugar conversion processes

Fuel		Stochiometric yield [kg fuel kg^{-1} sucrose]+	Fuel market value [$ kg^{-1} fuel]	Sugar cost [$ kg^{-1}]
Carbon	$C_6H_{12}O_6 \rightarrow 6\ C + 6\ H_2O$	0.421	0.014[a]	0.0059
Syngas/ methane	$C_6H_{12}O_6 \rightarrow 6\ CO + 6\ H_2$ $C_6H_{12}O_6 \rightarrow 3\ CH_4 + 3\ CO_2$	0.281	0.127	0.0356
Ethanol	$C_6H_{12}O_6 \rightarrow 2\ C_2H_6O + 2\ CO_2$	0.538	0.372[b]	0.200
Butanol	$C_6H_{12}O_6 \rightarrow C_4H_{10}O + 2\ CO_2 + H_2O$	0.2598++	1.325[c]	0.344

+Sucrose being converted to invert sugar (fructose/glucose)
++Due to by-products, butanol is produced typically at maximum 60% of the total solvent yield
[a] EIA (2018b)
[b] USDA (2018a)
[c] Zullo (2016)

technical and economic feasibility of converting molasses into ethanol, they all (directly or indirectly) acknowledge the lack of cost competitiveness with corn-derived sugars (Lipinsky 1976; Polack et al. 1981; Rein 2004; USDA 2006). Even the existing corn ethanol plants cannot sustain themselves by producing ethanol alone; they survive by selling the product mix of ethanol, carbon dioxide, and dried distiller's grain (produced at a 1:1 ratio with ethanol).

Bagasse, a coproduct of sugarcane processing, is often falsely declared a waste. It is used as a fuel for the raw sugar factory, and two integrated factories in Florida are also employing it as the fuel for their refineries. As such, its value is based on its energy content. Its composition is typically assumed to be $CH_{1.5}O_{0.7}$ and yields on average a gross calorific value of 19,410 kJ kg^{-1} (Chen and Chou 1993). Normally the heating value is depressed due to moisture and ash content. In Louisiana, the average bagasse composition (50.7% moisture, 3.3% ash) would mean a heating enthalpy of 9362 kJ kg^{-1}, which equates to 0.189 kg of natural gas and a value of \$0.024 kg^{-1} (Ehrenhauser et al. 2018). This value seems quite favorable for advanced fuel production; however, chemical conversion of biomass through pyrolysis, gasification, or catalytic upgrading is challenging due to the high variability of the material and/or the lack of cost competitiveness with fossil fuels in the US. Nonetheless, there are currently two pilot facilities operating in Louisiana converting bagasse.

American Biocarbon (Whitecastle, LA, USA) produces biocarbon from bagasse (American Biocarbon 2018). Based on the sum formula, the maximum yield would be 49% carbon from pure bagasse. Unfortunately, the presence of ash challenges the product, as the removal of water (and loss of carbon) from the bagasse raises the ash level accordingly, reducing the quality of the produced fuel. High-quality bagasse (low ash and low moisture) is therefore desirable for this process. In Raceland, Louisiana, Stora Enso operates an acid digestion-based pilot plant, which produces xylose and glucose (Stora 2018). However, their main product is xylose intended as a feedstock for xylitol and chemicals. Both facilities utilize excess bagasse, i.e., bagasse exceeding the energy need of the neighboring raw sugar factory, and function therefore as an offset to bagasse handling/disposal cost to the raw sugar factory.

Based on the fact that bagasse is already a fuel, it seems obvious to point out that any conversion will come with a loss of material and energy content, i.e., value. As such, direct thermal utilization through combustion for heating purposes and electric power generation seems to be the most viable path for bagasse to energy conversion in the USA.

14.2.3 Second-Generation Biofuel Production

Bioenergy from lignocellulosic biomass is one of the most promising options having minimal impact on food and water resources, land use, and the ecosystem (Manochio et al. 2017). According to a study supported by the United States (US) Department of Energy (DOE) and the US Department of Agriculture (USDA), the United States has the capacity to support the production of 1.3 billion dry tons of biomass annually if dedicated energy crops could be developed, grown, and harvested sustainably (Perlack et al. 2005). The United States has put in place initiatives to promote the commercial production of second-generation ethanol. These initiatives were developed under the Energy Policy Act of 2005 and were published as the Renewable Fuel Standard (RFS), which was later updated by the Energy Independence and Security Act (EISA) of 2007 (EPA 2018a). These policies mandate increasing the volume of biofuels to be blended into gasoline and diesel, while providing a premium price for biofuels based on a credit system known as renewable identification number (RIN) (EPA 2018b). A RIN is a 38-digit numeric code that singly identifies each gallon of renewable fuel that is produced in or imported into the US throughout the supply chain and separated from the renewable fuel upon blending with either gasoline or diesel (Klein-Marcuschamer and Blanch 2015). RINs can be used to comply with the RFS mandates or traded into economic incentives. This has created tensions between the renewable fuel and the fossil fuel producers and importers arguing that consumers should use the fuel of their choice without government interference and that the mandates create a blend wall where the current infrastructure cannot support blends higher than 10% (Oller 2014). In the USA, ethanol can be blended with gasoline up to 10%, this gasoline blend is referred to as E10, and it requires no major technological adjustments to the existing infrastructure or motor vehicles. However, for a biofuel producer to be profitable after the blend wall is reached, higher biofuel blends and more fuel-flexible cars must be available as well as consumer demand (Klein-Marcuschamer and Blanch 2015). Although a 15% gasoline blend (E15) has been approved by the US Environmental Protection Agency (EPA) for use in light-duty conventional vehicles model year 2001, no agreements have been reached between the oil refiners, vehicle producers, and the biofuel industry (Valdivia et al. 2016). This has become a key argument in support of drop-in fuels or advanced hydrocarbon biofuels (i.e., gasoline, diesel, and jet fuel) from lignocellulosic biomass, that is, fuels that would not require a change in the distribution and consumption infrastructure.

An ethanol production target was set for 136 billion liters of renewable fuels by 2022 with a cellulosic mandate of 60 billion liters (EPA 2018a). In 2007, DOE announced a loan guarantee scheme for the construction of six commercial-scale biorefineries with various processing technologies to meet these targets (Table 14.3). The major goals were to make ethanol from nonfood biomass (including agricultural residues such as sugarcane and energy cane bagasse) at a price competitive to gasoline and to increase the use of renewable and alternative fuels. The support of the US government toward the commercialization of second-generation fuels has been significant but has not been sufficient. A commercial scale has an output of at least 25 million liters of biofuel per year (Sims et al. 2010). As of February 2018, there were no commercial-scale second-generation ethanol facilities fully operational (Table 14.3). Only Poet-DSM remains committed to converting agricultural residues (mainly corn stover) into renewable fuel. The US second-generation ethanol projected capacity at the end of 2017 was estimated at 220 million liters with only six million liters registered (Ramos et al. 2016; USDA 2018c), an outcome that can be attributed to the biorefineries still facing processing challenges as well as not

Table 14.3 US second-generation commercial-scale biorefineries and current status

Company	Location	Biomass	Process	Projected output	Invested (loan)[a]	Status
				Million liters per year	Million USD	
Abengoa	Hugoton, Kansas	Corn plant and agricultural residues	Enzymatic hydrolysis	95	400 (132)	Filed for bankruptcy (2016)
Alico	Vero Beach, Florida	Yard, wood and vegetative waste	Syngas fermentation	30	300 (33)	Sold technology to INEOS Bio (2008); INEOS Bio plant sold to Alliance (2017)
BlueFire renewable	Fulton, Mississippi	Municipal cellulosic waste	Concentrated acid hydrolysis	72	300 (49)	Not known construction activity (2011)
DuPont	Nevada, Iowa	Corn stover	Enzymatic hydrolysis	114	200	Closed down (2017)
Iogen	Idaho Falls, Idaho	Agricultural residues	Enzymatic hydrolysis	68	200 (80)	Canceled construction (2008)
POET-DSME[b]	Emmetsburg, Iowa	Corn stover	Enzymatic hydrolysis	91	250	Operational/ adjacent to corn ethanol facility
Range fuels	Soperton, Georgia	Wood chips	Gasification	150	320 (76)	Closed down (2011); sold to LanzaTech

[a] Loan received from U.S. DOE

[b] POET was awarded a $105 million loan from U.S. DOE but declined it when it partnered with DSM

Janssen et al. (2013), Hayes (2016), Lane (2016, 2017), Hirtzer and Renshaw (2017), USDA (2018c)

being cost competitive with first-generation ethanol and fossil fuels, despite the financial incentives put in place. Second-generation ethanol production has also been affected by shale gas, a source of natural gas that has affected US natural gas prices, increasing demand and driving down prices (Janssen et al. 2013). Second-generation ethanol production can allow for the high-value utilization of hemicellulose, lignin, and process by-products to offset the costs associated with ethanol production (Fang et al. 2018). Some companies originally designated for the ethanol market (i.e., Blue Fire Renewables, Virdia (acquired by Stora Enso) Gevo, Amyris, Codexis, LS9 (acquired by REG Life Sciences, LLC), Virent) have shifted their research focus and plan to target the specialty chemicals market instead. A strategy is required that would allow these companies and the like to take advantage of the revenues from the specialty chemicals market until second-generation ethanol technologies become cost competitive to those of fossil fuels and are ready for commercialization.

14.2.4 Cogeneration of Electricity

14.2.4.1 Cogeneration from Sugarcane

Cogeneration in the cane sugar industry in the United States has been done primarily to satisfy the industry's internal power needs while only few factories have entered into agreements to sell electricity to utility companies. The installation of cogeneration facilities to sell electricity to the grid in Louisiana has been hampered by the poor CHP (combined heat and power) policy climate, allowing utility companies to charge high standby power rates and make the interconnection process more difficult (Chittum and Kaufman 2011). Six out of eleven sugar factories in Louisiana operate turbogenerators with capacities between 0.8 and 4.5 MW, for a total capacity of 14.3 MW (Spieker 2017). The largest producer, Lafourche Sugars, is the only one configured to sell electricity to the utility. It generates about 4.5 MW, of which most is used by the factory and typically less than 0.5 MW is sold. Lafourche Sugar's cogeneration project was initiated due to the existence of a pilot program from the Louisiana Public Service Commission to restudy the feasibility of implementing a renewable portfolio standard. After obtaining input from the utility companies participating in the program during 3 years, a mandatory renewable portfolio standard was not recommended in 2013 (Louisiana Public Service Commission 2013).

In Florida, all four sugar factories cogenerate, with the installed or permitted capacities ranging from 9.4 to 128.9 MW, for a total of 221.4 MW. The United States Sugar Corporation (US Sugar) facility has installed a capacity of 70 MW (US DOE 2018). Typically, less than 10% of the power production is sold to the utility. Okeelanta Power LP has a capacity of 128.9 MW (US DOE 2018). It is the only sugar mill configured to sell most of its electricity to the utilities. During the crushing season, the bagasse provides about two-thirds of the factory's power needs. Bagasse is complemented with wood chips, with a higher percentage during off-season (Monroe and McConnell 2014) to meet the electricity demand for the utilities. The only sugar mill in Texas, Rio Grande Valley Sugar Growers Inc. factory, has three 2.5 MW and a 16 MW backpressure unit. In normal operation, only the 16 MW unit is used, and it produces 9–10 MW, of which about 8 MW are consumed internally with 1–2 MW being supplied to the utilities. The utility payments to the factories for the power they receive are very low—usually only about $0.02/kWh. The Hawaiian sugar industry has ceased to exist. However, in the early 1970s, when there were over a dozen factories in operation, the Hawaiian sugar industry embarked on a major cogeneration effort. The factories installed high-pressure boilers (3.1–8.3 MPa), condensing/extraction turbogenerators, and utilized quintuple effect evaporator schemes with triple vapor bleeding to maximize their cogeneration potential. Many of the Hawaiian factories were able to sell about 5–15 MW to the utilities at good prices.

14.2.4.2 Cogeneration from Energy Cane

Energy cane varieties in Louisiana have the potential to produce between 206.9 and 277.1 kWh/t by burning the bagasse, containing 50% moisture, after processing in a conventional sugar mill. The released variety Ho 02-113 can produce 110 MW when it is processed at a rate of 10,000 t/day during 120 days (Aragon et al. 2015). Energy cane has not yet been widely adopted as a bioenergy source in the US, although its use has been encouraged by the US Department of Energy. The availability of data across the supply chain and the lack of distribution infrastructure for biofuels are among the barriers to its adoption.

14.3 Economics of Bioenergy Production

This section presents some economic estimates of the potential costs of utilizing sugarcane as a biofuel feedstock in both first- and second-generation ethanol production in the United States, as well as some factors which may limit the use or expansion of the use of sugarcane and energy cane as a biofuel feedstock. The specific region of focus presented here is for sugarcane production in Louisiana, a major sugarcane-producing state in the United States.

14.3.1 Biofuel Costs

The USDA conducted a major study in 2006 to evaluate the economic feasibility of producing ethanol from sugar in the US (Shapouri and Salassi 2006). Ethanol production cost values were estimated utilizing a variety of sugar source feedstocks including sugarcane, sugar beets, molasses, raw sugar, and refined sugar. Total ethanol production costs utilizing various sugar feedstocks were compared to corn ethanol production costs utilizing both wet milling and dry milling processes. Given the relative relationship between commodity market prices of raw sugar and corn, estimated ethanol production costs per liter of ethanol were higher utilizing various sugar sources as feedstocks compared with the use of corn as the major feedstock. Ethanol production costs utilizing sugar feedstocks were estimated to be \$0.63 l^{-1} utilizing sugarcane juice as the major feedstock, while production costs utilizing molasses or raw sugar as the major feedstock were estimated to be \$0.34 l^{-1} and \$0.92 l^{-1}, respectively. Estimated ethanol production costs utilizing corn in wet milling and dry milling processes were \$0.27 and \$0.28 l^{-1}, respectively.

Current estimates of ethanol production costs utilizing sugarcane juice as a feedstock were developed for the Louisiana sugarcane-producing region of the USA. These estimates are presented in Table 14.4 and are based on a typical sugarcane yield of 89.6 mt ha^{-1} (harvested) and a raw sugar recovery rate of 115 kg of raw sugar mt^{-1} of sugarcane. Molasses volume is based on a rate of 0.25 l kg^{-1} of

Table 14.4 Estimated costs of producing ethanol from sugarcane in Louisiana, USA

Production/cost factor	Unit	Value
Sugarcane yield per harvested area	mt ha^{-1}%	89.6
Percent of total farm area harvested[a]	%	76%
Sugarcane yield per total farm area	mt ha^{-1}	68.1
Raw sugar recovery from sugarcane	kg mt^{-1}	115.0
Raw sugar yield per total farm area	kg ha^{-1}	7834
Sucrose from raw sugar	%	96.0%
Sucrose from sugarcane per total farm area	kg ha^{-1}	7521
Molasses yield per total farm area	kg ha^{-1}	2760.5
Sucrose from molasses	%	49.2%
Sucrose from molasses per total farm area	kg ha^{-1}	1358
Total sucrose from sugarcane and molasses	kg ha^{-1}	8879
Total sucrose recovery rate	%	13.0%
Ethanol yield from sucrose[b]	l mt^{-1}	588.1
Ethanol yield per total farm area	l ha^{-1}	5222
Sugarcane production costs[c]	\$ ha^{-1}	\$1357
Land rent[d]	\$ ha^{-1}	\$395
Processing costs	\$ ha^{-1}	\$1569
Total production and processing costs	\$ ha^{-1}	\$3321
Ethanol cost per liter	\$ l^{-1}	\$0.64

[a] Sugarcane harvested through third stubble with 24% of total farm area in fallow/plant
[b] Assumed practical ethanol plant conversion rate
[c] Variable and fixed sugarcane production costs for Louisiana for the crop year 2017
[d] Land rent charged at a one-sixth crop share rate after deduction of processing crop proceeds

raw sugar. For sugarcane production cycle through harvest of a third stubble crop, 76 percent of total farm area would be harvested in a given year. Farm operations on the remaining farm area would include fallow and planting activities. Sugarcane production costs utilized in the evaluation were for the 2017 crop year (Deliberto et al. 2017).

With this level of sugarcane production per hectare and assuming typical sucrose extraction rates for raw sugar and molasses, the total sucrose production would be 11,681 kg ha^{-1} (harvested) and 8879 kg ha^{-1} of the total farm area, and the total ethanol production potential for this case scenario would equal 5222 l ha^{-1} of the farm area. At current crop production costs for sugarcane in Louisiana, costs of producing ethanol from sugarcane juice were estimated to be \$0.64 l^{-1} of ethanol, similar to cost estimates from the earlier USDA study. The use of sugarcane juice as a feedstock in traditional ethanol production in the USA has not been economically viable relative to corn grain. As a result, much of the focus of research and development has recently focused on the potential for feedstock such as high-fiber energy cane to serve as a biomass feedstock in cellulosic biofuel production.

14.3.2 Biofuel Feedstock Costs

Several research studies over the past few years have been conducted to evaluate the relative economic feasibility of utilizing high-fiber energy cane varieties of sugarcane as a potential biomass feedstock in the production of cellulosic ethanol or other advanced biofuels. These studies have focused on the estimation of the cost of the energy cane biomass as a feedstock input into cellulosic biofuel production.

Salassi et al. (2014) explored the crop establishment and whole farm production costs of growing energy cane as a biofuel feedstock in the southeastern USA. Variable production costs for energy cane production were estimated to be in the \$63–\$76 mt^{-1} range, and total production costs were estimated to range between \$105 and \$127 mt^{-1} of feedstock biomass dry matter material. Mark et al. (2014) compared the estimated feedstock costs of energy cane as a cellulosic biofuel feedstock input and made comparisons to costs of producing ethanol from corn grain. The study concluded that varietal improvements that would provide higher biomass yields and longer crop stubbling ability in energy cane were the most likely means of improving the economic feasibility of biofuel production from energy cane relative to corn.

Another study evaluated the potential for the expansion of energy cane production as a biofuel feedstock over a six-state region in the southeastern USA (Salassi et al. 2015b). Within the southeastern region of the USA, approximately 10.9 million ha of agricultural land exist in the current crop production. Another 1.15 million ha of croplands were estimated to be available for the potential expansion of energy cane production. The study reported that the estimated biofuel feedstock costs for energy cane could decline substantially if higher yielding energy cane varieties could be developed.

Concentration of the biofuel feedstock crop production in specific regions of the USA is dependent on the relative comparative advantage of production in a specific region based on several agronomic and economic factors (Salassi et al. 2017). For the southeastern region of the USA, energy cane, among a few other crops, has been identified as a feedstock crop with the greatest potential for further development of production. Field trials evaluating alternative varieties of high-fiber energy cane through several years of stubble crop production have recently been completed to allow for a more accurate estimation of biofuel feedstock costs utilizing energy cane.

Estimates of energy cane crop yields utilized in this study were taken from energy cane variety field trials conducted at the Louisiana State University AgCenter Sugar Research Station in St. Gabriel, Louisiana (Gravois et al. 2014). Five alternative varieties of energy cane were planted in 2008 in research plots on the station. These plots were harvested over the next 6 years to estimate the yield for the plant

Table 14.5 Feedstock production acreage requirements to supply fixed daily biomass quantity

Crop production phase	Feedstock crop harvest yield (mt ha^{-1})	Feedstock production acreage requirement[a] (ha)
(1) Energy cane through third stubble	90.56	12,982
(2) Energy cane through fourth stubble	88.66	13,261
(3) Energy cane through fifth stubble	87.74	13,400

[a] Production area required to meet a daily feedstock requirement for processing facility specified to be 13,063 harvest weight (mt day^{-1}), based on a processing rate of 544 mt h^{-1} at 24 h per day. Example for a Louisiana harvest season of 90 days, October 1 through December 31

Table 14.6 Estimated feedstock production costs for alternative cropping sequences

	Feedstock production scenarios[a]		
Estimated feedstock costs	1	2	3
	(\$ h^{-1})		
Variable cost	1028	1049	1064
Fixed cost	330	332	333
Total production cost	1358	1381	1397
Land rent at break-even revenue[b]	272	276	279
	(\$ mt^{-1} harvest weight)		
Variable cost	11.35	11.83	12.13
Fixed cost	3.64	3.74	3.80
Total cost	14.99	15.57	15.92
Land rent	3.00	3.11	3.18
Total cost plus rent	17.99	18.69	19.11
	(\$ mt^{-1} harvest weight)		
Variable cost	61.54	60.69	\$58.88
Fixed cost	19.76	19.21	\$18.45
Total cost	81.31	79.89	\$77.33
Land rent	16.26	15.98	\$15.47
Total cost plus rent	97.57	95.87	\$92.80

[a] Scenario 1 = 90-day processing season, energy cane harvested through third stubble; Scenario 2 = 90-day processing season, energy cane harvested through fourth stubble; Scenario 3 = 90-day processing season, energy cane harvested through fifth stubble

[b] Land rent charged at a rate of one-sixth crop share at break-even revenue

cane crop (harvested in 2009) and the first stubble through fifth stubble crops (harvested in 2010 through 2014).

For three alternative energy cane feedstock production sequences, the production area required to supply a processing facility with a fixed daily supply of feedstock biomass over a specified harvest season is shown in Table 14.5. The processing capacity utilized here is similar to what currently exists for sugarcane processing in Louisiana, USA. With a processing capacity of 544 mt h^{-1} and a daily processing period of 24 h, the daily feedstock requirement for a processing facility at this specified capacity would be 13,063 mt day^{-1}. It would require approximately 13,000 ha of energy cane to supply a processing facility for a 90-d processing season. Estimates of variable and fixed production costs taken from values for the 2015 crop year for sugarcane in Louisiana were used to develop these energy cost estimates (Salassi et al. 2015a).

Current estimates of energy cane feedstock production costs per area and per output unit are shown in Table 14.6 for three cropping sequences (harvest through third stubble, fourth stubble, and fifth stubble). Total production costs for energy cane feedstock production were estimated to range from \$1358 to \$1397 ha^{-1}. On a unit of biomass output basis, production costs per meter of harvest weight were estimated to be in the range of \$17.99 to \$19.11 mt^{-1}. Whereas, on a dry weight basis, estimated feedstock costs of energy cane as a biofuel feedstock input were estimated to range between \$92.80 and \$97.57 dry mt^{-1}.

14.4 Challenges and Opportunities for the Use of Sugarcane and Energy Cane for Bioenergy in the USA

While it is estimated that around 30% of world ethanol production comes from sugarcane (REN21 2016), there are no commercial enterprises producing ethanol from sugarcane or energy cane in the USA (USDA 2018c). The value of sugar as a sweetener is the primary reason it is not used commercially for conversion to liquid fuel. The relative economic disadvantage of sugar feedstock sources compared with corn grain in traditional ethanol production has been, and continues to be, a major limiting factor for the use of a feedstock such as sugarcane juice to produce biofuel in the USA (Shapouri and Salassi 2006).

Predictions of world food shortages make land use changes to accommodate the expansion of bioenergy crop production problematic. World population is predicted to exceed 11 billion inhabitants by 2100, an increase of almost 50% (UN 2017). Reductions in the food supply would likely be concomitant with farmland diversion for the production of dedicated biomass crops. However, the use of idle cropland that is not occupied by commercial crop production presents an opportunity for the production of sugarcane and energy cane biomass feedstocks in the subtropical environment of the lower southern states (Salassi 2015).

Expansion to more northerly latitudes beyond the confines of the sugar-growing region would require enhanced cold tolerance. Experimental sugarcane and energy cane clones with improved cold tolerance have been identified, and progress is being made to develop genetic markers to breed varieties for cultivation outside of the traditional geographic zone of production (Hale et al. 2017; Khan et al. 2013). Other major issues associated with the expansion of the cultivation of sugarcane or energy cane as biomass crops for biofuel production include impacts on air, soil, and water quality, allocation of water resources, and deforestation. These and other issues are addressed in a comprehensive overview of cultivating sugarcane for use in bioenergy applications (Sandhu 2018) and its use as a renewable energy resource from a sustainable production perspective (Johnson et al. 2018).

A sugar factory stream currently in excess of the internal needs for fuel is bagasse. Based on the known bagasse production and consumption as a factory fuel, it is estimated that approximately a million metric tons of bagasse are available for use for the development of other energy sources like second-generation ethanol, pelletized fuel, biochar, or other forms of energy or bio products. Sugarcane crop residue captured in the field or at the processing facility represents another potential biomass source for the production of energy. Harvest residue dry matter ranged as high as 19.6 Mg ha^{-1} in a long-term harvest residue study conducted by Viator and Wang (2011). Failure to return crop residue to the field, however, could undermine the sustainability of sugarcane production. Cherubin et al. (2018) recently reviewed the implications of harvest residue removal and discussed opportunities to mitigate its negative effects.

The Brazilian model of broadening out to use sugarcane as a renewable energy crop may not be repeatable in the USA primarily because of the relatively high cost of using sugar feedstocks for ethanol, but energy cane and other sources of lignocellulosic biomass are promising feedstocks for the production of ethanol. There are, however, still several challenges at each processing step of ethanol conversion which has prevented second-generation biorefineries to be commercially available to date. Biorefineries will require a consolidated bioprocessing approach using pretreatment, enzymatic degradation, and fermentation which can efficiently and completely utilize the biomass. In addition to ethanol, the production of other by-products from lignocellulosic biomass holds great potential for increasing the value and usefulness of biofuels. The future success of second-generation ethanol will require dependable financial incentives and supportive regulations, which are instrumental in driving the commercial production and adoption of second-generation ethanol.

14.5 Conclusion

Bioethanol in the USA is made from corn and not from sugarcane or energy cane feedstocks. The higher value of raw and refined sugar relative to corn makes sugarcane ethanol not economically feasible. Molasses is the possible exception, as its cost at times is competitive with the cost of corn. Molasses supply, however, is limited due to long-standing contractual commitments primarily with the animal feed industry and a challenge due to the lack of proximity of raw sugar factories to corn ethanol biorefineries. Continuation of the US sugar program, which serves to support and stabilize prices, diminishes the likelihood of sugarcane being used for conventional fermentation to ethanol. More promising is the production of second-generation ethanol from energy cane. Federal government initiatives have encouraged the commercialization of second-generation ethanol through mandated biofuel volume targets. But challenged by low fossil fuel prices, processing issues, and relatively high costs, second-generation biofuels have yet to achieve commercial status. A sustained commitment to sugarcane and energy cane biofuel research and development is needed to overcome the challenges being faced by this industry which would help yield a profitable market in advanced biofuels.

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Chapter 15
Sugarcane Biofuel Production in South Africa, Guatemala, the Philippines, Argentina, Vietnam, Cuba, and Sri Lanka

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15.1 Introduction

Substantial sugarcane industries exist in South Africa (SA), Guatemala, the Philippines, Argentina, Vietnam, Cuba, and Sri Lanka. Despite not being the largest from a global perspective, these industries still have significant footprints in agriculture and rural economic development of these countries. A diversity of activities occur in the sugarcane value chain, from agriculture through transport and the manufacture of raw and refined sugar, syrups, and specialized sugar by-products and coproducts. The sugarcane industries in these countries have potential to contribute significantly to bioenergy and biofuel production. The present chapter considers the situation in each of these countries with regard to biofuel and electricity coproduction from sugarcane.

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15.2 South Africa

15.2.1 Status of the Sugarcane Crop in the Country

Sugarcane is a strategic agricultural crop for South Africa with a production capacity of more than 20 million tons per annum. Sugarcane is grown by approximately 24,000 registered sugarcane growers farming predominantly in KwaZulu-Natal with substantial operations in Mpumalanga, and some sugarcane production in the Eastern Cape. Sugar is manufactured by six milling companies with 14 sugar mills operating in the cane-growing regions. The industry produces an average of 2.2 million tons of sugar per season (March–December). Approximately 75% of this sugar is marketed in the Southern African Customs Union (SACU), while the remainder is exported to markets in Africa, Asia, and the United States, as reported by South African Sugar Association (SASA 2017).

The 10-year (2006–2016) trend of sugarcane production and area harvested based on the reported data by the Food and Agriculture Organization (FAO) are shown in Fig. 15.1. A considerable decrease can be seen in annual production and harvested areas, mostly due to changes in rainfall. For instance, 2015/2016 season was affected by the severe drought experienced in Southern Africa. The season was extremely poor in terms of tons of cane harvested, which decreased by 16% from 2014 to 2015 and 26% since 2013 to 2014 (Smith et al. 2016).

Currently, South Africa is the world's 18th largest sugar producer, with sugar being the second largest agricultural export. In 2006, South Africa was ranked at the 14th position in the world (FAOSTAT 2017). The lower production rate is not only because of severe drought but also inefficient performance of the sugar mill factories (Dogbe et al. 2018).

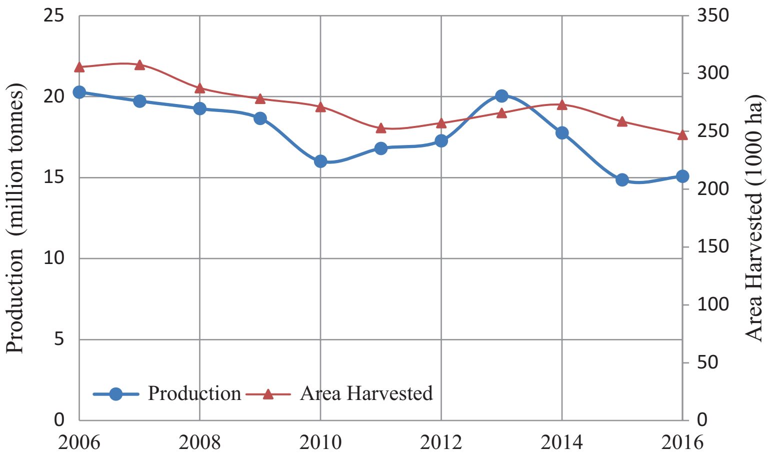

Fig. 15.1 Trend of sugarcane production and area harvested in South Africa during 2006–2016. (FAOSTAT 2017)

In addition to sugar, molasses and bagasse are the other by-products from sugarcane produced in typical South African sugar mills. Molasses contains considerable amounts of sucrose (approximately 32–42%), and can be sold in liquid or dried form as a commercial feed ingredient. Sugarcane molasses is also used for alcohol production; moreover, the distillery process yields vinasses that find applications in fertilizer production or animal feeding. Sugarcane molasses has several important roles in livestock feeding, due to the nutritive, appetizing, and physical properties of its sugar content. Molasses is difficult to handle because of its viscosity: it is rarely fed directly in its liquid form but instead mixed with other ingredients such as bagasse (Feedipedia 2018).

Sugarcane bagasse (fibrous fraction of cane after sugar extraction) is the most abundant crop residue produced globally and this resource can be increased by harvesting the sugarcane leaves and tops. Typically 15% of sugarcane is bagasse (dry matter), and leaves account for additional 7.5% of the biomass (Petersen et al. 2014). The use of sugarcane harvesting residues (mostly brown leaves; also called trash) has the added benefit of not competing as a food source and has a similar energy content as bagasse per unit weight. However, trash is frequently burnt off to facilitate harvesting of the stalks, thus not realizing its potential as a significant source of energy.

15.2.2 The Sugar Industry of the Country

Statistics South Africa (STATSSA 2018) reports that the South African sugar industry generates an annual estimated average direct income of over US$1 billion, and contributed about 0.3% of South Africa's GDP in 2016, based on revenue generated through sugar sales in the SACU region as well as world market exports. The industry makes an important contribution to employment and sustainable socioeconomic development, particularly in rural areas. This is built on its agricultural and industrial investments, foreign exchange earnings, labor intensity, and linkages with major suppliers, support industries, and customers. It is a diverse industry, combining the agricultural activities of sugarcane cultivation with the manufacture of raw and refined sugar, syrups, and specialized sugar by-products and coproducts (Petersen et al. 2017). The sugar industry has the potential to be a producer of renewable energy, biofuels, and bioplastics (Farzad et al. 2017b; Mandegari et al. 2017a, b).

An important feature of the sugar industry is employment in rural and deep rural areas in job-starved regions, where there are often few economic opportunities. Direct employment occurs both in the sugarcane field and the sugar mills and ranges across a diverse array of skills from the farm laborer to agricultural scientist. The sheer size of economic activity generated in rural areas through the activities of sugarcane cultivation and sugar production also generates a vast number of jobs in support industries and commerce. In most cases the sugar mill and accompanying cane farms form the backbone of the nearest rural town and are major contributors to the development of secondary economic activities, and services and infrastructure that otherwise would be absent. A unique relationship exists between sugarcane and sugar production, as cane is a bulky, non-tradable commodity which requires rapid postharvest processing in order to preserve the sucrose in the cane stalk. As a result, sugar mills are always located as close as possible to the cane-supplying zones. The financial viability of these significant capital investments is entirely dependent on a sustainable supply of sugarcane in each mill supply area.

The sugar industry creates approximately 79,000 direct jobs, which represents over 11% of the total agricultural workforce in South Africa. Additionally, registered cane growers supplying cane to the sugar mills also earn from this sector. Indirect employment is estimated to be 350,000 jobs (SASA 2017). Approximately one million people or 2% of South Africa's population depend on the sugar industry for a living (Alimandegari et al. 2017).

15.2.3 Bioenergy Production from Sugarcane in South Africa

Historically, agriculture has been recognized as being an engine for economic growth that can have a strong impact on poverty and hunger reduction. Bioenergy could be an option for stimulating agricultural sector growth, leading to further socioeconomic development and poverty alleviation around the industry, especially through smallholder farmers (Maltsoglou et al. 2013). Sugarcane is increasingly targeted for bioenergy production (Peng et al. 2014). The most important biofuel to date is bioethanol produced from sugars—sucrose and molasses (Petersen et al. 2017).

A bioenergy crop should optimally be high yielding, and fast growing. Moreover, its processing requirements should be low and it should need relatively small energy inputs for its growth and harvest. Sugarcane is the most efficient bioenergy crop of tropical and subtropical regions, and biotechnological tools for the improvement of this crop are advancing rapidly (Waclawovsky et al. 2010). With developments in sugarcane harvesting and cogeneration technology, bagasse and sugarcane trash have become important sources of bioenergy in some countries such as Brazil. Second-generation bioethanol is also being targeted for studies to allow the use of the cell wall (lignocellulose) as a source of carbon for energy production (Alimandegari et al. 2017).

15.2.4 Existing and New Facilities (Case Studies) for Industrial Biofuel Production

South Africa has traditionally been an energy exporter, primarily in the form of coal-derived electricity. However, in recent years, demand has started to outstrip supply and alternative cleaner energy sources are needed (Aghbashlo et al. 2018).

South Africa's history of using biofuel dates back to the 1920s when sugar ethanol was blended with petrol (Blanchard et al. 2011; Pradhan and Mbohwa 2014). The blending was halted in the early 1960s due to cheaper imported fossil fuels, which made blending economically unviable. In 2007, South Africa tried to revive biofuels by developing the Biofuels Industrial Strategy. The strategy proposed adoption of a 5-year pilot program to achieve a 2% penetration level (previously the target was 4.5%) of biofuels in the national liquid fuel supply, equivalent to 400 million liters per annum (van Zyl et al. 2011). The proposed crops were sugarcane and sugar beet for bioethanol, while maize was excluded on the basis of food security concerns. Former homeland areas were proposed for such cultivation and an estimated 1.4% of arable land was implied to achieve a 2% penetration (Maltsoglou et al. 2013). However, this strategy has not been implemented because of changing global petroleum prices and a plethora of non-technological constrictions that hindered biofuel adoption and development. Even some existing molasses to ethanol facilities (e.g., Komati Sugar Mill) have not been operational due to economic unviability (Smith et al. 2016).

Production of ethanol to anhydrous (E10) specification is expensive and will not be feasible without some form of government subsidy or financial incentives. It may, however, be feasible to produce ethanol at 95% purity (suitable for E95 blending), but this will require a parallel distribution network for liquid fuel, or conversion of a dedicated fleet to E95 specification (Hugo 2016). Therefore, there are currently no existing operational or new facilities in South Africa for commercial ethanol production for biofuel applications. Existing ethanol production is utilized to serve markets for potable or beverage-grade ethanol, as well as export markets for green chemicals. Future economic conditions may favor opportunities to utilize the fiber component of cane, in particular for renewable electricity production (Peng et al. 2014). Limited capacity for electricity cogeneration do exist at some sugar mills; however, favorable market prices and incentives for renewable energy do not exist to expand its production.

15.2.5 Lignocellulosic Conversion to Electricity and Biofuels

It is estimated that ~2.5 Mt per annum bagasse is produced in South Africa, most of which is currently burnt in inefficient boilers, to provide the steam and electricity to sugar mills. Further, the tops (green leaves) and trash (dry brown leaves) harvesting residues of sugarcane are mostly burnt on-field, with brown leaves alone (50% of harvesting residue) representing another 1.3 Mt per annum of lignocellulosic feedstock (Smithers 2014; Petersen et al. 2017). This biomass has potential to be converted into 1 Mt per annum bioethanol via biochemical processes (Alimandegari et al. 2017), or export up to 420 MW of electricity if converted efficiently into electricity (Petersen et al. 2017). However, harvesting residues are not available for the mentioned utilization due to current practices of burning cane before harvest. Although, adoption of "green" harvesting will make some of the residue available, it may have a significant negative impact on rural livelihoods as some of the green cane harvesting is likely to be automated. Furthermore, sugarcane bagasse is currently used for low-efficiency energy generation. Therefore, to liberate bagasse for additional energy generation (for biofuel production), capital investment in new boiler-turbine technology will be required (Dogbe et al. 2018).

15.2.6 Challenges and Future Perspectives

Biofuels have a potential to extend and diversify South Africa's energy supply, thus reducing dependence on imported fuels and pollution levels. Developing biofuels is a big challenge to the government of South Africa due to issues related to food security, commodity prices, economic and social concerns, and impacts of land use changes on the environment (Rosen 2018). The production cost of feedstock and employment creation opportunities from agricultural production play a vital role in selecting suitable feedstock for the region. Therefore, further research is required to address these concerns.

The potential of biofuels to fulfill energy and economic security has renewed the public and political interest on biofuels. The government of South Africa established the Biofuels Industrial Strategy in 2007 to address the renewed interest on the need for biofuels in the country, while a successful program to introduce renewable electricity to the national grid has largely excluded the sugarcane industry. Despite several biofuel policies and mandates, biofuel development in South Africa has stalled in the legislative process, and no large-scale commercial biofuel project has materialized yet (Pradhan and Mbohwa 2014). Since considerable investment and infrastructure will be required for continuous supply of feedstock and efficient biomass conversion technologies, rigorous research and comprehensive studies are being carried out to identify feedstock and technologies best suited for the successful establishment of biofuel industry in South Africa. In Table 15.1 some of the recent techno-economic studies on the sugarcane biorefineries for biofuel, biochemical, and biopolymers in South Africa are given.

On the other hand, South Africa stands as the largest sugarcane producer in the African continent. Approximately 3–7 tons of molasses can be produced from 100 tons of fresh sugarcane. Therefore, it is estimated that about 1 Mt per annum molasses is being produced as by-product of the processing in the South African sugar factories. There is a potential of 0.3 Mt per annum bioethanol production via sucrose fermentation of molasses. All of the molasses produced by the industry is presently utilized in either (potable/beverage grade) ethanol production or used for livestock feeding.

Table 15.1 Some of the recent techno-economic studies on the sugarcane biorefineries in South Africa

Feedstock(s)	Product(s)	Yield (weight % fuel/feedstock)	Reference
Bagasse and trash	EtOH	26.0%	Alimandegari et al. (2017)
Bagasse and trash	Butanol	11.8%	Farzad et al. (2017b)
Cane juice, bagasse, and trash	Jet fuel	10%[a]	Diederichs et al. (2016)
Bagasse and trash	MeOH/FT syncrude	25.8–29.4%/8.4–12.2%	Petersen et al. (2015)
Bagasse	Pyrolysis products	19.2–30%	Nsaful et al. (2013)
Bagasse and trash	EtOH/butadiene	21.8–33.5%/7.0–8.8%	Farzad et al. (2017a)
Bagasse and trash	EtOH/lactic acid	33.5%/49.3%	Aghbashlo et al. (2018)
Cane juice, bagasse, and trash	EtOH/electricity	5.03–21.8%	Petersen et al. (2017)
Bagasse and trash	Gasification products	20–70%	Farzad et al. (2016)
Bagasse and trash	Butanol	5.6–10.5%	Haigh et al. (2018)

[a] Yield for cane juice to jet fuel: 48%

15.2.7 *Concluding Remarks*

The South African sugarcane industry has long pursued the options of biofuels and renewable electricity production, as a means to expand its revenue streams and ensure future sustainability of the industry. However, these efforts have not managed to secure sufficient market opportunities to warrant substantial commercial expansions in the production of either, primarily due to the requirement for substantial financial incentives from the government to ensure viability of these investments.

15.3 Guatemala

15.3.1 *The Sugarcane Crop in Guatemala*

Sugarcane is produced on the far-eastern and Pacific coasts of Guatemala, with the majority of production taking place on the latter. The current national production of sugarcane in Guatemala is about 28.1 million tons per annum, harvested on an area of 270,000 hectares (Tay 2017). Guatemala's agricultural land is the most productive in the world for its yield of sugarcane (Souza et al. 2018), with the current active area of 270,000 hectares has a productivity of 104 tons of sugarcane per hectare. The agricultural land productivity has drastically improved over time due to continuous improvement and research, as the agricultural area and productivity had been 100,000 hectares and 66 tons per hectare, respectively, 30 years ago (Tay 2017).

15.3.2 Sugar Industry: Sugar and Ethanol Production

There are 14 sugar mills operating in Guatemala, 13 of them being on the Pacific zone and the remaining on the eastern region (Tay 2017; Tomei 2015). With the sugarcane production rate of 28.1 million tons per annum and a milling season of 6 months, the average daily crushing rate is 12,000 tons per day, with the Pantaleon mill being the largest at 29,000 tons per day (Pantaleon 2018).

The primary product of the mills is raw sugar, and the total production on an annual basis is about 2.8 million tons (Cairns Group 2016; Tay 2017). The mills are regarded as being highly efficient, with a sugar production rate of about 100 kg per ton of cane, which represents a recovery of about 74% of the initial sugar content of the cane toward sugar. This recovery used to be about 85% around 2009, but has dropped as the steer toward ethanol production from sugarcane had increased. Of the 14 mills, 5 of them cogenerate ethanol from molasses for a combined annual production of 269 million liters (CentralAmericaData.com 2014; Tay 2017), which is mostly exported to Europe. The production of ethanol has been rapidly expanding due to the increased demand by the European Union for biofuels, as production had increased by 33% since 2011, which is equivalent to an average annual expansion of 4.8% (Tay 2011).

15.3.3 Cogeneration of Electricity

The sugar mills in Guatemala generate electricity all the year-round, instead of only during the harvesting season when bagasse is available. This is achieved by the use of high-efficient flexi-fuel boilers that utilize bagasse during harvest and fossil fuel (such as bunker fuel) during the growing season (Johnson and Seebaluck 2013). The combined installed capacity of the mills is about 574 MW (Tay 2017) during the harvesting season, which is normally reduced by about 32% (Johnson and Seebaluck 2013) during the growth season when fossil fuel is used. The expansion of the electricity generation has also been quite rapid, as it expanded by about 85% since 2011 (Tay 2011), which is equivalent to an annual average expansion of about 10.8%. This increase is a combination of two factors, i.e., the increase in sugarcane throughput and installment of more efficient energy generation equipment.

15.3.4 Challenges and Future Perspectives

From a technical and economic viewpoint, not much can be said about any direct challenges regarding the expansion of sugarcane bioenergy and bioethanol industry in Guatemala, as the growth of either product has been expanding rapidly through the last decade(s). There is, however, little potential land left for continued expansion of the sugarcane crop (Tay 2017). Thus, if Guatemala is to expand its capacity for ethanol production, the remaining sugar-only mills will require annexed distilleries for ethanol production from molasses, or the conversion of lignocelluloses to ethanol.

The challenges in Guatemala's biofuel production lie predominantly in the socio-environmental sphere, which range in issues pertaining to land access of the general population, labor practices, and water pollution (Tomei 2015). Most of the land in Guatemala is owned by "elite" families and generally the farmers rent land from these elites for their own livelihoods, which for many Guatemalans means micro-farming for self-sustenance and small-scale commercial activities. As the interests in sugarcane farming for biofuels increased due to the economic lucrativeness in the Guatemalan context, land accessibility for such activities by the general population decreased (Tomei 2015). There is also a general lack of labor unions to enforce fair labor practices on the harvesting fields and in the mills, due to the intimidation that labor union members face. Furthermore, the industry reduced the efficacy that labor unions may have, by favoring the use of casual workers over permanent employees (Tomei 2015).

Poor water quality is a major concern for the public health in Guatemala, and the sugarcane industry is one of the major contributors to the pollution of natural water resources. This arises mostly because of the wash-off of fertilizers and herbicides from the sugarcane fields, and untreated effluents from the mills (Conley et al. 2010). Furthermore, the sugarcane production and processing industries are one of the major users of freshwater in the country, limiting its access to the underprivileged population (Conley et al. 2010).

15.3.5 Concluding Remarks

Guatemala is one of the top sugar exporters in the world; however, it is not likely that sugar production would increase in the country since the land availability for sugarcane agriculture is saturated. The steer toward bioethanol production for exports to the EU could further decrease the sugar production as it competes for the same raw material. From technical and economic perspectives, the sugarcane industry in Guatemala thrives, given its high capacity of sugarcane agriculture, the balanced production of sugar and ethanol, and the efficient cogeneration of electricity from sugarcane residues that contributes to the national grid.

Both ethanol and electricity production has been expanding rapidly over the last few decades, given the need for greenhouse gas reduction by the use of bioenergy. Legislative policies and their enforcement by the state, however, are urgently needed to mitigate the socio-environmental consequences caused by the rapid expansion of sugarcane operations. These are needed to ensure fair land access for the largely impoverished Guatemalan population, fair labor practices on the sugarcane fields and in the milling operations, and to abate the pollution of the country's water resources by the sugarcane industry. Failure to implement such reforms could cause the perceiving of Guatemalan biofuel as a product of exploitation, negatively affecting its reception by the EU member states.

15.4 Cuba

15.4.1 The Sugarcane Crop

Historically, Cuba has been one of the world's leading sugarcane producers as, prior to 1990, Cuba processed 82 million tons of sugarcane per annum (Alonso-pippo et al. 2008). Then, due to poor policies, unrealistic targets, geopolitical changes (Alonso-pippo et al. 2008), degrading infrastructure, and natural disasters, Cuba's sugarcane production dropped to 12 million tons per annum by 2006 (Pollitt 2010). In the 1970s, national targets to produce ten million tons of sugar had been set by the Cuban government against the advice from experts in agriculture (Alonso-pippo et al. 2008). This led to mismanagement and inefficient practices on the entire production chain of sugar, which in turn led to very high production costs (Alonso-pippo et al. 2008; Patiño 2009; Pollitt 2010).

The high production costs did not bear any consequences to the Cuban government while under Soviet patronage (Alonso-pippo et al. 2008; Patiño 2009), as such patronage assured that Cuba would receive 4 tons of oil per ton of cane it exported (Alonso-pippo et al. 2008). However, with the dissolution of the Soviet Union in the early 1990s, this patronage ended (Alonso-pippo et al. 2008; Patiño 2009; Pollitt 2010). Thus, Cuban sugar was forced into the international markets, where it could not compete economically, and as a consequence, sugar production had to be downscaled as the subsidies required for large-scale production would have crippled the economy (Alonso-pippo et al. 2008; Patiño 2009; Pollitt 2010).

From 2002, the Cuban government instituted a program to revitalize the sugarcane industry by reforming the agricultural and milling practices, in order to reduce the production costs of sugarcane. Thus, production was downscaled even further as the program could only focus on the lucrative harvesting areas with the most efficient mills (Alonso-pippo et al. 2008; Patiño 2009; Council on Hemispheric Affairs [COHA] 2017). The progress of the reformation program, however, met with catastrophe when in 2005, the worse hurricane to have ever struck Cuba in modern history destroyed many of the cane fields (Alonso-pippo et al. 2008; Patiño 2009). The recovery from this disaster has been slow due to lack of resources and required infrastructure improvements which the Cuban government could not afford (Patiño 2009). Between 2005 and 2015, the cane production experienced a minor growth.

15.4.2 Sugar Industry: Sugar and Ethanol Production

The current sugarcane production of 15 million tons per annum (COHA 2017) is about 18% of its historical (highest) production in Cuba. At the moment, there are only 70 mills operating in Cuba, out of the 156 that used to be operational under Soviet patronage (Alonso-pippo et al. 2008; COHA 2017). The mills were originally built in 3 size categories—of which 82 were in the range of <3000 tons per day (crushing capacity); 48 were in the range of 3000–6000 tons per day; and 26 were in the range of >6000 tons per day (Alonso-pippo et al. 2008). Thus, at the current (2016) crushing rate of 15 million tons per annum, the mills have an average crushing rate of about 1300 tons per day, which is far below their intended scales.

The current sugar production in Cuba amounts to no more than the local consumption of 700,000 tons per annum (Alonso-pippo et al. 2008), and Cuba imports sugar to satisfy the local demand. Sugar recovery in Cuban mills is 71%, which is rather low considering that there is currently no competing use such as ethanol production for sugars in the country (Alonso-pippo et al. 2008). Ethanol production from molasses had been practiced at only 16 mills (Alonso-pippo et al. 2008), and the highest annual production on record is about 26 million gallons (COHA 2017). Currently, no ethanol produced in Cuba is used as biofuel for transportation (COHA 2017).

15.4.3 Cogeneration of Electricity

For most of the mills in Cuba, the bagasse generated through cane crushing is burnt in low-efficiency boilers with pressure ratings of 10–20 bars, to provide steam needed to drive the process (Alonso-pippo et al. 2008). Thus, most of the mills are dependent on the grid for the needed electrical energy. For the mills which possess cogeneration capacity, the total production of generated electricity amounts to about 600 MW, of which 5% is exported to the grid (Alonso-pippo et al. 2008).

15.4.4 Challenges and Future Perspectives

The primary challenge facing the Cuban government's plan to rejuvenate the cane fields is the amount of fertilizer required, which cannot be sustained by the current state of its economy. Fertilizer is an import for Cuba, and its purchase was downscaled as the economy shrunk. Also, importing of new or refurbished harvesting equipment that is needed is not affordable to the Cuban economy (Pérez-López 2016). Furthermore, the micro-road infrastructure connecting farms and mills needs to be upgraded to improve the efficiency of cane transportation (COHA 2017).

As noted earlier, the mills themselves are operating far below their intended scales due to the limited supply of sugarcane. It was also noted that the mills have a low sugar extraction rate and that most of the mills are very energy-inefficient in terms of electricity cogeneration. However, it is estimated that replacing the low pressure boilers with high pressure boilers can improve the cogeneration capacity from 600 MW to about 1500 MW (COHA 2017). Ethanol production in Cuba has also been limited because of the government policies, as it was perceived that ethanol production competes with food production (COHA 2017). As there is no evidence of ethanol production in Cuba currently, it is probable that the 16 mills in which ethanol was produced previously have been shut due to the shortage of cane (Alonso-pippo et al. 2008).

The rejuvenation of the sugarcane industry in Cuba requires an inflow of foreign funds through investments into the sugarcane industry (Alonso-pippo et al. 2008; COHA 2017). Such funding is required for the much-needed fertilizer for expanding crop growth, importing harvesting machinery, and upgrading of infrastructure as well as sugar mills. Further investments will also contribute toward improving the efficiency of the mill operations and augmenting the cogeneration capacity (Sapp 2014).

15.4.5 Concluding Remarks

The dilapidated state of the Cuban sugar industry clearly demonstrates the adverse consequences of disregarding established agricultural and industrial practices and the overdependence of an industry's success on a certain geopolitical situation. The trade agreements between Cuba and the Soviet Union had formed the backbone of the Cuban economy, and the lucrativeness of this deal on the Cuban end had caused complacency as far as industrial and agricultural practices in the sugar were concerned. As soon as the geopolitical situation altered, the sugar industry became unsustainable.

The Cuban economy and the sugarcane industry are effectively caught in a vicious circle, as the Cuban economy's dependence on its sugarcane industry had crippled it, while on the other hand, the imports of the necessities to revive the sugar industry is not affordable to the Cuban economy. Thus, the only means of reviving the economy is to allow foreign investment directly into the sugarcane industry to provide the funding for importing of the capital and consumables needed to boost sugarcane production and improve the current state of technology. A sugarcane industry that is in a poor technological state cannot make any meaningful contribution to bioenergy, as the mills should have an acceptable operating efficiency before bioelectricity can be exported to the grid. Furthermore, the current governmental policies in Cuba toward ethanol production for use as transportation biofuels should be reconsidered.

15.5 Argentina

15.5.1 *The Sugarcane Crop*

The sugarcane fields are primarily located in the northwestern regions of Argentina, and the total production of the country was 25 million tons in 2016. Sugarcane is used for both raw sugar and ethanol production in Argentina (Joseph 2016). In the last 10 years, there has been no significant increase in the amount of cane grown, as there had only been a total increase of about 11% (Joseph 2011). However, since 2010, the amount of cane used directly for ethanol production has increased from about 2% in 2010 to about 23% in 2016 (Joseph 2011, 2017).

15.5.2 *Sugar Industry: Sugar and Ethanol Production*

There are 20 large sugar mills built in Argentina, with 15 being in the Tucuman region and 5 in the Salta region (Joseph 2011), Out of these mills, 9 mills currently coproduce ethanol (Joseph 2017). With a 6-month harvesting period from May to November (Braier and Marenco 2018), the average crushing rate is about 7000 tons cane per day for each mill, with the smallest mills operating at 1000 tons cane per day and the larger mills operating at 10,000s tons cane per day (The Sugar Engineers 2018).

The annual sugar production by the end of 2016 harvesting season was 2.1 million tons (Joseph 2016). This is a considerable reduction of about 13% from the 2009 harvest (Joseph 2010), due to increasing crop usage for ethanol production. Ethanol was traditionally only produced from molasses, but has increasingly been produced directly from sugarcane juice, as it has been offering better returns to the milling operations (Joseph 2017). The ethanol produced from sugarcane amounts to about 525 million liters per annum, and contributes about 46% to the total ethanol produced in Argentina (Joseph 2017). In addition to the 525 million liters produced for fuel, a further 80 million liters is produced for nonfuel applications, such as pharmaceuticals and beverages (Joseph 2017). Since 2011, the total ethanol production has increased by a factor of about 8, which was mainly achieved by using cane juice directly for ethanol production (Joseph 2017).

15.5.3 Cogeneration of Electricity

Most of the mills in Argentina burn bagasse as a means of disposal in low-pressure boilers with back pressure turbines to provide the steam and electricity needs of the plant. However, four mills generate electricity efficiently enough to sell a surplus to the grid (Mele et al. 2013a, b). While it was not possible to obtain an exact value for the total installed capacity for electricity generated from bagasse, it is estimated that the proportion of total available bagasse in Argentina that is transformed for electricity generation amounts to only 19% (UN Data 2018). Thus, the potential to increase the capacity of electricity production by the sugarcane industry by at least fourfold exists predominantly in upgrading the mills' equipment to improve energy efficiency.

15.5.4 Challenges and Future Perspectives

As a member of the Paris Agreement on Climate Change and an attendee of COP-22, Argentina is committed to reducing its greenhouse gas emissions by 18% unconditionally by 2030, and 30% conditionally by the same year (Joseph 2017). Two possible manners through which this target may be achieved is by (1) implementing the share of 20% renewable electricity mix before 2025 and (2) instigating high biofuel blends of ~25% or greater (Joseph 2017). For achieving either target, the sugarcane industry plays a pivotal role as a large-scale producer of biofuels and bioelectricity, and the Argentinian government incentivizes ethanol production and bioelectricity generation through tax cuts and premiums (Global Data 2017; Joseph 2017).

As the mills in Argentina can generally be regarded as inefficient, the challenges facing the sugarcane industry lie predominantly in the upgrading of sugar mills in terms of their energy consumption vs. efficiency of the cogeneration energy circuit. Thus, it is expected that a number of projects aimed to improve the installed electricity generation capacity of the sugarcane industry will commence in order to meet the target for the share of renewable electricity in the national Argentinian electricity grid. One such project is already in progress, as the La Florida mill is currently in the process of installing a 45 MW cogeneration plant (Sugaronline.com 2018). These projects, however, are very capital intensive and might require foreign investments to provide funds.

In order to meet the short-term increased blending target from 10% to 12% that was mandated in 2016, three sugar mills are in the process of being upgraded to produce an extra 150,000–200,000 liters of ethanol per day (Joseph 2017). As higher blending ratios such as 85% ethanol are mandated in the long run, it is likely that the remaining sugar-only mills will install distilleries, and that more sugarcane will be used directly in ethanol production. However, this will also mean that vehicles in Argentina will require flex-fuel engines (Joseph 2017).

15.5.5 Concluding Remarks

The sugarcane industry in Argentina contributes considerably to the country's commitments to reduce greenhouse gas emissions by a significant extent through biofuel production and insignificantly through bioelectricity production. To increase the production of ethanol, for fulfilling the demand created by mandating of higher blending ratios of biofuel to fossil fuel, more of the existing mills will require annexed distilleries that convert molasses into ethanol. Else, increasing ethanol production by increasing the direct use of sugarcane juice for ethanol will reduce the sugar production. With regard to bioelectricity generation, and its contribution by the sugar mills of Argentina toward the clean energy targets, investments are required to revamp the technological status of the mills, by installing high-efficiency cogeneration equipment.

15.6 Vietnam

15.6.1 Status of Sugarcane Crop in the Country

Sugarcane is an important industrial cash crop in Vietnam. It was introduced in the southern areas of the country in the early twentieth century. Later, it was planted in the central and Mekong river delta regions (Vietbid 2001). Thus, the area planted with sugarcane has been increasing over the years. According to Vietnam Sugar Association, the current sugarcane plantation occupies an estimated area of 305,000 hectares (Hieu 2016). Some large-scale farms, ranging from 10 to 15 hectares of land, also cultivate sugarcane. The crop is a source of employment and income to more than 337,000 sugarcane-growing families (Nguyen 2017).

Vietnam's average cane yield in 2017 was 64.4 tons per hectare with 10% sugar content (Nguyen 2017; Toan et al. 2016). Despite significant improvement in the crop productivity, sugarcane faces many challenges including climate change, extended drought, outdated varieties, and slow adaptation of new technology in the country. Thus, the Vietnam government is working on improving the quality of both cane yields and sucrose, with significant research efforts to develop varieties with early maturity, high sugarcane yield, and increased sucrose content (Toan et al. 2016).

Figure 15.2 depicts annual production of sugarcane from 2005 to 2015. Although the plantation area increased from 266,331 to 301,900 ha between the period, the crop production has not improved. The production was low for the 3 consecutive years (2008–2010) due to severe droughts (Toan et al. 2016). The production started to increase again from 2011 and reached the highest of 19.82 million tons in 2013. The production for 2015 was also slightly low compared to that of 2014 due to decrease in plantation area (284,500 ha) (Trinh and Linh Le 2018).

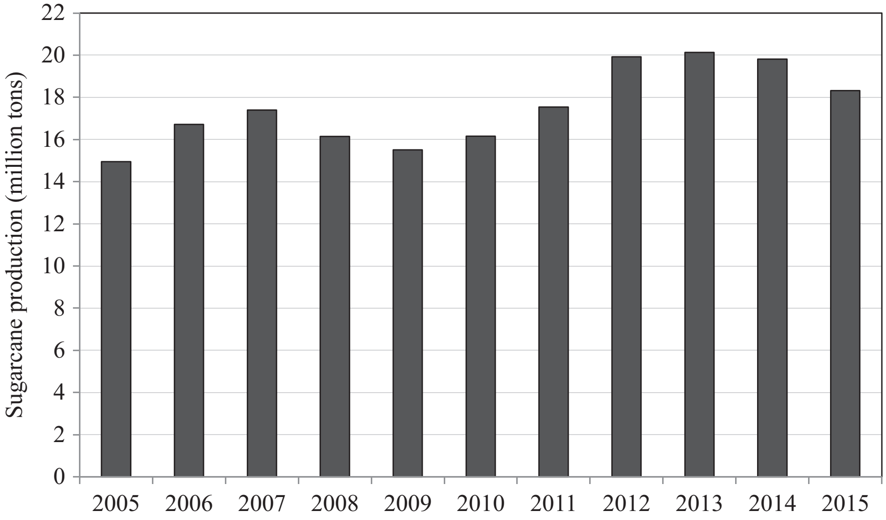

Fig. 15.2 Production of sugarcane in Vietnam from 2005 to 2015. (STATISTA 2018)

15.6.2 Sugarcane Industry: Sugar and Ethanol Production

Sugarcane is the second largest crop for bioethanol production after cassava in Vietnam. Bioethanol production at large scale uses molasses from sugar mills as a raw material. Currently, there is only one factory that uses a combination of cassava and molasses to produce ethanol. However, the contribution of ethanol from molasses is very small (3–6%) (Trinh and Linh Le 2018). About 100 million tons of ethanol is produced annually in Vietnam. Molasses normally contains approximately 40 and 45% sugar (Hieu 2016). Vietnam has 41 sugar mills which can generate around 3.6 million tons of sugarcane molasses annually (Van Loc 2016). The molasses produced from these mills can be used to engender up to 912 million liters of bioethanol.

Moreover, the government of Vietnam is encouraging policies to support development of biofuels since 2003 (Asian Biomass 2013). In 2007, the National Energy Development Strategy to 2020, with vision to 2050, was developed to boost the development of new renewable energy to replace the use of fossil fuels. To achieve this goal, short-, medium-, and long-term strategies were formed, including (1) improving research and development, (2) establishing strong industry that utilizes agriculture products to produce biofuels, (3) developing policies and framework that will attract investors (local and foreign) to establish vibrant biofuel industries, and (4) promoting international cooperation to facilitate the biofuel sector (Trinh and Linh Le 2018). In this regard, government provided tax incentives for importation of new equipment for the local and international companies, and the companies were also given land for the period of 20 years.

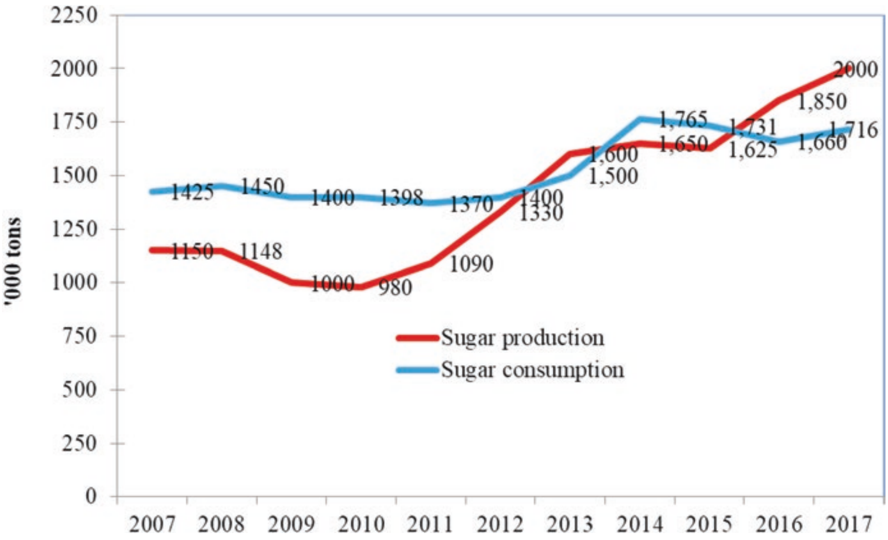

Fig. 15.3 Sugar production and consumption in Vietnam from 2007 to 2017. (USDA 2017)

In terms of sugar production, Vietnam has 41 sugar mills with total milling capacity of 139,800 tons of sugarcane (Nguyen 2017). About 70% of sugarcane is processed by small cottage industries, having limited capacity of less than 100 tons cane crushing per day. The remaining 30% is processed by commercial cane mills. The small-scale processing mills are located in the key areas where they can be easily accessed by the local growers. Nevertheless, the mills are highly inefficient due to high loss of sucrose and production of sugar with poor quality. Alternatively, farmers can transport the sugarcane to bigger commercial-scale mills, but the route is difficult and expensive.

The annual sugar production of the country in 2017 was 2.0 million tons (United States Department of Agriculture [USDA] 2017). The trend of sugar production and consumption in the country for the period of 10 years (2007–2017) is shown in Fig. 15.3. Sugar production has increased by 74% from 1.15 million tons in the last 10 years. However, sugar production for years 2009, 2010, and 2011 was less due to low sugarcane production (Fig. 15.2) caused by prolonged drought. Yet, in general, sugar production has increased more rapidly than the consumption during the past 10 years.

15.6.3 Challenges and Future Perspectives

The biofuel program in Vietnam remains important for its strategy of reducing CO_2 emissions in transportation sector. However, the implementation of this program has been facing various challenges including low social acceptance and shutdown of biofuel plants due to low local demand. Since 2015, three biofuel factories have closed due to lack of local market. Similarly, the biofuel industry is facing technological barriers because most of the factory uses old technology compared to the foreign countries. Thus, biofuel plants are not cost competitive due to high energy demand. Moreover, availability of human resources is also a challenge as the biofuel industry requires skilled labor and experts to drive scientific research and development activities.

In order to increase biofuel uptake in the country, the government should mandate the blending program. Such blending program will lead to expansion of the sugarcane production and processing contributing toward Vietnam's mission to increase employment and enhance income for the rural communities. The government indicates that an additional 450,000 hectares are potentially available for sugarcane production (Van Loc 2016). Based on the current sugarcane yield of 64.4 tons cane per hectare, there will be additional 28.98 million tons of sugarcane available for processing to sugar or bioethanol. The expansion of sugarcane plantation is also expected to generate huge amounts of bagasse for ethanol engenderment and electricity cogeneration (Zwebe 2012).

15.6.4 Concluding Remarks

Despite present-day challenges, Vietnam remains optimistic about the potential to expand both sugarcane cultivation and bioethanol production, which will require substantial new investments into the industry, in both existing and new sugar mills. The associated increase in economic activities is likely to bring socioeconomic development to the rural communities where these industries are located, or launched.

15.7 Philippines

15.7.1 Status of Sugarcane Production in the Country

Sugarcane is one of the major crops in the Philippines. It is cultivated in 20 provinces across the country. The crop is grown in more than 62,000 farms occupying an estimated area around 420,000 hectares, which is 7.43% of arable land (Bautista-Martin 2012). The majority of the farms (81%) are operated by small-scale holder farmers (0.01–5.00 hectares) (Anon 2016). One hectare of sugarcane usually requires 15 workers. This means that the labor force directly employed by the industry, including sugar mills and refinery, is around 700,000 with the additional five million indirectly dependent on sugar production for livelihood.

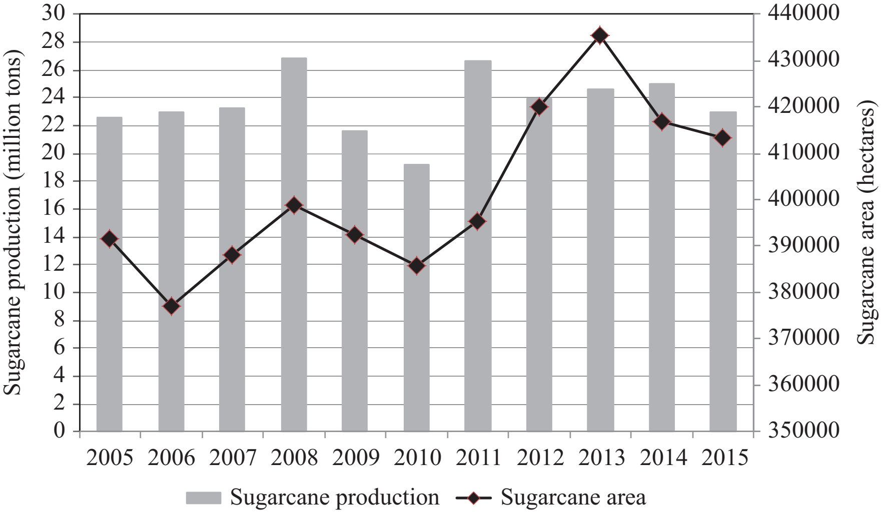

Fig. 15.4 Sugarcane production and sugarcane area from 2005 to 2015. (Bautista-Martin 2012; STATISTA 2017)

Figure 15.4 shows the trend of sugarcane production and the area cultivated for the period of 10 years (STATISTA 2017). The average annual production is around 23.6 million tons. The lowest crop production was observed in year 2010 (19.2 million tons) when the country experienced El Niño drought. On the other hand, the highest production was observed in 2008 (26.9 million tons). Generally, the increase of farming area did not improve crop production in many instances. This could be attributed to inadequate investments and climate change in recent years (Shrivastava et al. 2011). The latter is expected to continue hampering any increase in sugarcane production. In an attempt to facilitate sugarcane production, the Sugarcane Industry Development Act (RA 10659) was signed into law in March 2015 in response to inadequate sugarcane production and inefficient milling operations. The Act provided US$43 million for infrastructure support program, research and development, socialized credit, grants to block farmers, and scholarship grants (Corpuz 2017).

15.7.2 *Sugarcane Industry: Sugar and Ethanol Production*

The sugar industry in the Philippines is a multiproduct industry with sugar, bioethanol, and power as its major products. The country has 29 sugar mills with an average milling capacity of 185,000 tons cane per day (Corpuz 2017). The country also has 14 operating sugar refineries with total refining capacity of 8800 tons per day (Anon 2016).

In terms of sugar production, the production has been 2.4 million tons for the last 10 years (USDA 2017). Most of the sugar produced is for the local market. However,

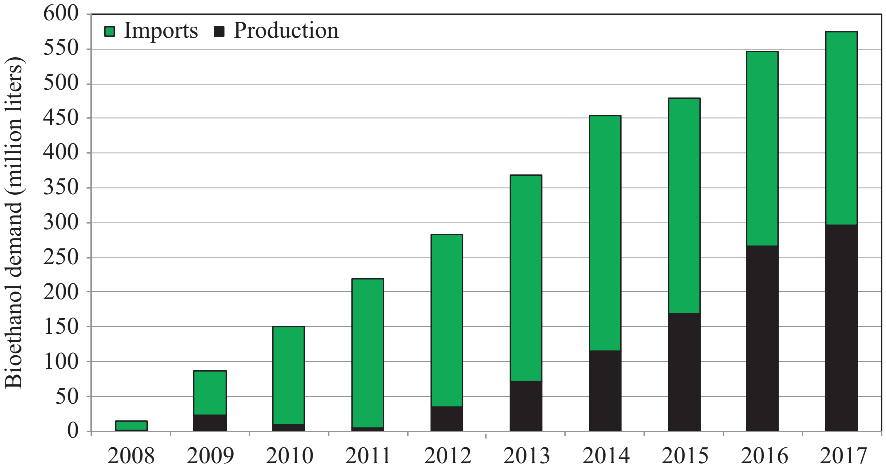

Fig. 15.5 Production and importation trend of bioethanol from 2008 to 2017. (Corpuz 2017)

the country also set aside about 200,000 tons for export to the United States, which is considered as a favorable market. Generally, the industry produces sufficient amount to meet the domestic demand. Consequently, any expansion in the industry is meant for bioethanol production. Nevertheless, sometimes El Niño brings extended drought damaging the crop resulting in poor yields.

The history of bioethanol production in the Philippines can be traced back to 2006 when the Bioethanol Act opened the gates to new investments in the sugarcane industry through bioethanol production facilities. In 2007, voluntary 5% bioethanol blend in petrol was implemented and the ethanol employed for the purpose was imported from abroad (Corpuz 2017). The first biorefinery with a capacity to produce 30 million liters of bioethanol annually was opened in 2009 by San Carlos Bioenergy. The number of bioethanol plants had reached 11 by 2017, with a total capacity of 322 million liters.

Figure 15.5 depicts the production and importation trends of bioethanol for the past 10 years (2008–2017). The production shows exponential growth from 0.364 million liters in 2008 to 296 million liters in 2017. The observed growth is driven by the Biofuels Act. The said law mandated oil companies to blend bioethanol with petrol at 5%. Currently, the fuels distributed by companies in the community are blended with 10% bioethanol. The blending ratio will be increased to 20% by 2020, with an ultimate target to achieve a blending of 85%, according to the National Renewable Energy Program.

Nevertheless, the local demand is considerably higher than the production. The current local production can only supply around 52% of the demand, and the remaining portion has to be imported. The United States is a leading exporter of ethanol to the Philippines. In 2015, the country spent over $170 million to buy ethanol from the United States. Overall, bioethanol imports, however, declined by

10.6% to 261 million liters from 311 million liters in 2015 due to increase in local bioethanol production.

15.7.3 Challenges and Future Prospects

The sugar industry of the Philippines faces various challenges including sugar tariff variation, poor performance of sugar mills, profitability uncertainty, and implementation of biofuel and renewable energy laws. The country has also been facing prolonged drought in recent years, hence affecting the sugar industry. The research and development efforts are being carried out to develop new varieties of sugarcane with intrinsic properties of early maturity, high yield, and improved sugar content. The research also explores the possibility of using the bagasse as a feedstock for second-generation ethanol production. According to the bioethanol Act, the production of second-generation ethanol at commercial scale is expected to be realized by 2030.

The implementation of biofuel law has created a sustainable market for locally produced bioethanol. However, the current capacity cannot supply the demand. To address the gap, the fuel companies import their additional requirements from other countries preferably the United States and Brazil. Notably, significant efforts have been employed to increase the sugarcane production during the last 10 years. The area under the sugarcane plantation has increased from 391,552 hectares in 2005 to 413,264 hectares in 2015. However, these efforts do not reflect expected increase in sugarcane production (22.6–22.9 million tons). Furthermore, the current ethanol production process uses sugar molasses as the raw material (first-generation). The second-generation ethanol (ethanol from bagasse) needs to be integrated along with the first-generation production. The integration of second generation will add up to 40% of the ethanol produced from first-generation technology (Benjamin et al. 2014).

15.7.4 Concluding Remarks

The large local market for sugarcane-derived products, including bioethanol, is likely to continue driving the expansion of this industry in the Philippines. The booming of the industry was made possible by the biofuel law which mandate blending of ethanol with gasoline. The ultimate goal of the blending program is to reach 85% ethanol. There may also be potential to increase imports from nearby countries, to avoid the long-distance import of ethanol from the United States and Brazil.

15.8 Sri Lanka

15.8.1 Status of Sugarcane Crop in the Country

Sugarcane makes a significant contribution to the national economy of Sri Lanka by reducing the cost of sugar import. In 2012, the country spent a total $385 million on importing sugar (Kodituwakku 2013). Sugarcane is also a source of employment and income for the majority of people living along the farming areas and the sugar mills. Nevertheless, sugarcane yields per hectare have declined from its maximum of 66.9 tons to an average of 44.1 tons over the last 8 years (Fig. 15.6) (FAOSTAT 2017). The maximum yield of Sri Lanka has been lower than the average yields of other Asian countries such as India (67.3 tons per hectare) and Thailand (68.8 tons per hectare) (Keerthipala and Harmawardene 2000; Kodituwakku 2013). The likely reasons for this reduction could be the change of climatic conditions and the change of ownership of land from government to private sector. About 60% of the arable land in Sri Lanka is located in the dry zone (Keerthipala and harmawardene 2000). The sugarcane farms are normally rainfed or operated by irrigation. Low sugarcane yield is expected for the rainfed farms when prolonged drought occurs, consequently reducing the yield, harvested area, and the average sugarcane production per year (Fig. 15.6).

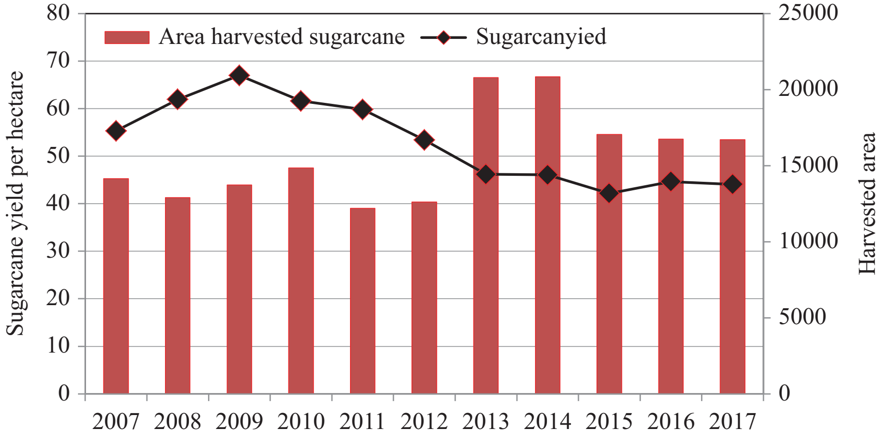

Fig. 15.6 Sugarcane yield per hectare and area harvested for sugarcane in Sri Lanka from 2007 to 2017. (FAOSTAT 2017)

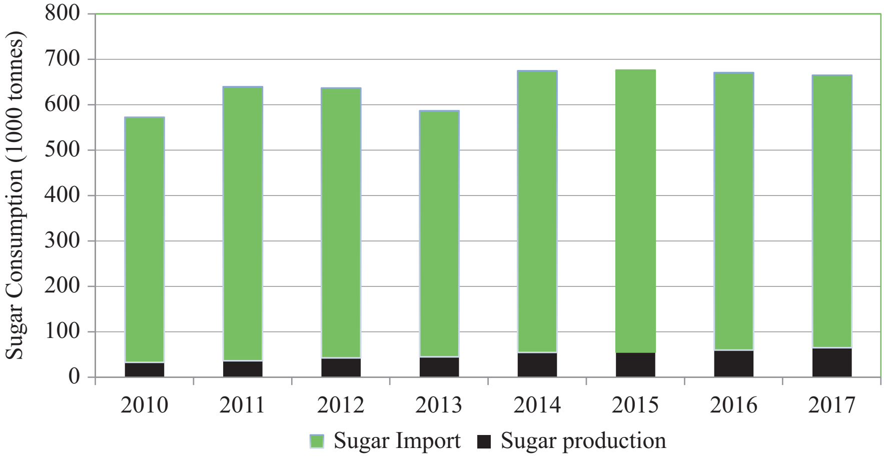

Fig. 15.7 Sugarcane production, import, and consumption in Sri Lanka from 2007 to 2017. (Keerthipal 2016; USDA 2017)

15.8.2 Sugarcane Industry: Sugar and Ethanol Production

Sri Lanka does not currently produce ethanol from sugarcane. However, the country is expecting to use the sugar molasses for bioethanol production in the future. Sugar industry of Sri Lanka is very weak and it is going to take many years before it could be able to produce enough sugar to meet the local demands. Sugar production is growing very slowly for the past 10 years (Fig. 15.7). The present total annual production of sugar is 65,000 tons, which is around 9.8% of the current annual demand of 665,000 tons (USDA 2017). Possible reasons for the slow growth could be due to closure of some of the mills due to civil war, change of management from public to private sector, unattractive policies in the sugar sector, and the variations in sugar prices. The country is lacking a coherent government policy to protect the interests of the stakeholders.

15.8.3 Challenges and Future Perspectives

There are many challenges for the sugar industry in Sri Lanka. The country uses old technologies and machines to manufacture sugar leading to high cost of production. The industry also faces shortage of skilled labor. Furthermore, the research and development has not been sufficient to increase cane production per hectare. Moreover, the country does not use full potential of by-products of the crop after sugar extraction. For example, the sugar mills do not use bagasse to produce electricity even for their own operation; rather the boilers use oil which enhance the cost of production. The cost of production must be lowered for sustainable growth of the sugar industry in Sri Lanka.

According to the Sugar Development Project announced in 2015 (Lanka Business Online 2015), Sri Lanka has planned to increase the area for sugarcane plantation and the number of processing mills from the current 4 to 19 (Keerthipal 2016). The plan aims that 50% of the sugar demand should be produced locally by 2020. This means that the country should produce around 500,000 tons of sugar annually (according to projected sugar requirement of one million tons by 2020). The country will need to cultivate sugarcane on around 113,000 hectares of land (based on the current sugarcane yield of 44.3 ton per hectare). Additional land of around 100,000 ha has been proposed for possible sugarcane expansion in Kurunegala, Budalla, Monaragala, and Hambantota districts. However, unfortunately, these plans have not been realized yet. A complete restructuring of the sugar sector is needed in this regard. All these problems are hindering any bioethanol production in the country. Government policies should also be related to bioethanol production rather than sugarcane production generally.

15.8.4 Concluding Remarks

The substantial local sugar demand, and limited local production, continues to create opportunities to expand both sugarcane and biofuel production in Sri Lanka. These will only be realized through a concerted effort to attract the necessary investment to estimate this potential. However, researches and studies on biofuel production can be commenced to define the most feasible approach for commercial implementation considering country's context.

15.9 Conclusion

In this chapter, the status of sugarcane biofuel production in South Africa, Guatemala, the Philippines, Argentina, Vietnam, Cuba, and Sri Lanka with ~9% of the global sugarcane production has been studied. The effective strategies in the mentioned countries should be placed to use the capacity and expand sugarcane industry, not only to produce more sugar for internal demand and export but also to move toward bioenergy production strategies for sugar industry valorization. Biofuels, particularly ethanol, have been expanding rapidly over the last few decades in some countries such as Brazil, the United States, and several EU states, given the need for greenhouse gas reduction and sustainable development. The road of sugarcane biofuel is being paved by such countries and the successful experiences can be used to expedite expansion of sugarcane biofuels. Legislative policies and their enforcement by the state, however, are also required to mitigate the socio-environmental consequences caused by the expansion of sugarcane industry considering biofuel extension.

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Part III

Industrial and Technological Aspects of the Sugarcane Bioenergy Production Process

Chapter 16
Source-Sink Relationship of Sugarcane Energy Production at the Sugar Mills

Sagheer Ahmad, Muhammad Anjum Ali, Giovanna M. Aita, Muhammad Tahir Khan, and Imtiaz Ahmed Khan

Abbreviations

5-HMF	5-Hydroxymethylfurfural
AFEX	Ammonia fiber explosion
BIGCC	Biomass integrated gasification combined cycle
BOD	Biological oxygen demand
BPST	Back pressure steam turbines
CBP	Consolidated bioprocessing
CEST	Condensation-extraction steam turbines
COD	Chemical oxygen demand
CTBV	Centrale Thermique de Belle Vue
DOE	Department of Energy
DW	Dry weight
FAO	Food and Agriculture Organization
FFV	Flex-fuel vehicles
GHV	Gross heating value
HRSG	Heat recovery steam generator
ISO	International Sugar Organization
MTBE	Methyl tertiary butyl ether
SHF	Separate hydrolysis and fermentation
SSCF	Simultaneous saccharification and cofermentation
SSF	Simultaneous saccharification and fermentation
USDA	United States Department of Agriculture

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Sugarcane is an important source of bioenergy. It has been widely grown for sugar production since long, however recently it has emerged as a promising bioenergy engenderment tool. Sugarcane can be exploited for producing ethanol from sucrose (first-generation biofuels), as well as from biomass (second-generation biofuels). It has great energy potential as it is an efficient crop in terms of fixing energy, and a huge biomass producer (Khan et al. 2017a). Moreover, sugarcane can also be utilized for bioelectricity production through cogeneration. Hence, sugarcane sucrose, bagasse, molasses, and sugarcane trash (collected from sugarcane field) can all be used for bioenergy fructification in one form or the other (Leal et al. 2013). This section details the use of various by-products of sugar industry for bioenergy production either in the form of ethanol as fuel for vehicles, heat for the industry, or biogas and bioelectricity for domestic and industrial use.

16.1 The Sugar Milling Process

The sugar production in a sugar mill goes through several steps including crushing of sugarcane, squeezing and separation of raw juice from bagasse, and juice clarification through heating and chemical reactants addition. Then, the juice is concentrated by heat inputs that boil it to evaporate moisture leading to the stage of crystallization. Finally, the crystallized sugar is separated from molasses through the process of centrifugation. Several by-products obtained during the manufacturing of crystal sugar are either disposed of into the environment endangering the ecosystem or utilized judiciously to make valuable products with less toxic waste materials. The major by-products of sugar industry are bagasse, molasses, pressmud, vinasse, furnace ash, and steam released during juice evaporation and condensation. Figure 16.1 shows a simplified scheme of the sugar mills process (Colombo et al. 2014; Toasa 2009).

All the steps carried out in a sugar factory require heat, electrical, and mechanical energy. Most of the mill processes' energy requirements are met out from its own energy source of bagasse acting as feedstock of energy units. The boilers are developed to burn bagasse at about 50% moisture for energy production that is used in the mill in different forms:

(i) The addition of hot water to shredded cane facilitates up to 96% sucrose extraction ravaging only 4% in bagasse during milling.
(ii) The juice is collected in tanks for liming/sulphitation, kept at proper temperature through heat exchange system, and then clarified from settled mud through filtration. This process involves precipitation of insoluble calcium phosphates of variable composition in hot melt liquor by adding phosphoric acid, followed by addition of calcium hydroxide slurry water (milk of lime) with a final pH of 7.2–7.4.
(iii) The clarified juice is evaporated in the evaporator tandem to concentrate the juice, whereas steam is evolved in sufficient quantities for use in various other stages of the process.

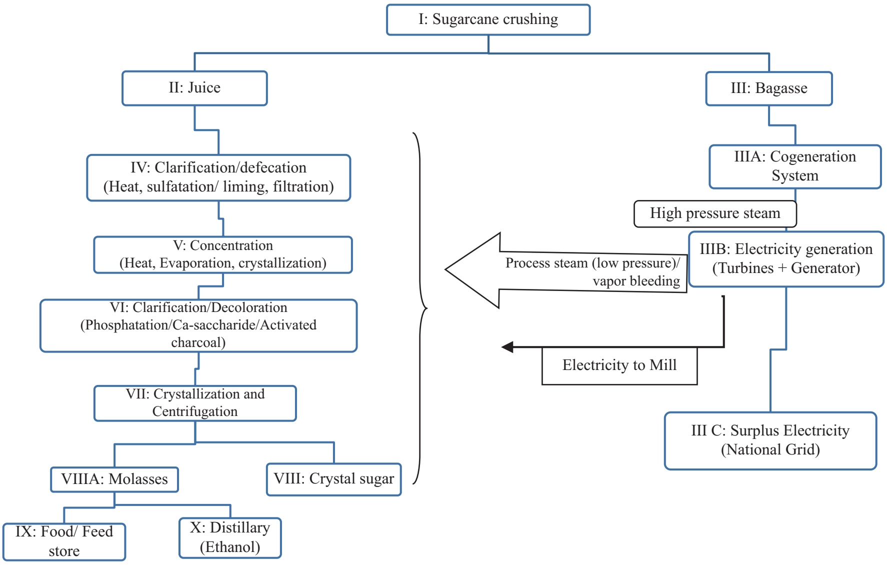

Fig. 16.1 A typical sugar factory's operations' schematic diagram (Colombo et al. 2014; Ensinas et al. 2006)

(iv) The concentrated juice is boiled in vacuum pans where low pressure and continuous provision of heat makes the juice supersaturated. This saturated syrup is termed as massecuite that comprises of crystals of sugar and molasses.
(v) Massecuite is passed through centrifugation process at centrifuge mills that separates sugar crystals from molasses.
(vi) Molasses are either used for the production of ethanol in distillery units or sent to the storage tanks for sale.
(vii) During sugar production, a lot of surplus heat energy is produced that is either dissipated or used for electricity production.

The general parameters of thermal energy usage in a typical cane sugar factory (Ensinas et al. 2006) can be characterized as follows:

(i) Raw juice leaves extraction system at 35 °C.
(ii) Juice clarification takes place by heating up to 103 °C yielding 14–16% Brix.
(iii) Treated juice enters the first stage of multi-effect evaporation system at 97 °C concentrating it from 15 to 65° Brix while reaching the fifth effect evaporation system. Absolute pressures of the evaporation stages are 1.69, 1.34, 0.98, 0.51, and 0.16 bars, respectively.
(iv) Syrup is continuously heated at 80 °C using steam from the first effect of evaporation station for treatment.
(v) Sugar syrup boiling into vacuum pans with steam from multi-effect evaporation station and concentrates to 91–93% Brix, which is termed as "massecuite."

(vi) Finally, centrifugation and separating of sugar from molasses take place.
(vii) Overall about 5% of steam is lost in the process.
(viii) Process steam is used at 2.1 bar pressure for sugar drying.

16.1.1 Bagasse

Bagasse is a fibrous residue generated by sugar industries after sugary juice extraction from sugarcane (Daud et al. 2007; Sun et al. 2004). Bagasse is a product of paramount importance in sugar mills' operations as a source of ethanol and bioelectricity. On an average, 280 kg bagasse is yielded on crushing of one ton sugarcane, although it varies from 220 to 360 per ton, primarily determined by its fiber, juice, and trash content. In a sugar factory, one ton of refined sugar corresponds to about two tons of bagasse production. Fresh bagasse is also called mill wet bagasse with 48–52% moisture, 48% fiber, and 2–4% sugar and other elements (Lois-Correa et al. 2010; White 2009). The energy value of bagasse basically depends on its fiber content that comprises 30–50% cellulose, 28–35% hemicellulose, 20–25% lignin, 5% sugars, and about 2% minerals on dry weight basis. At 50% moisture, the gross heating value (GHV) of mill wet bagasse is 9361.4 kJ kg^{-1} and of dry bagasse is 19,498 kJ kg^{-1} (Abdalla et al. 2018).

Major uses of bagasse at the sugar mills are enlisted as follows:

- Bagasse can be used for second-generation ethanol production at the sugar mills, which have great importance because of the fact that such kind of ethanol engenderment does not compete with sugar production (Khan et al. 2017b).
- Bagasse is used to fuel the sugar mill (Antaresti et al. 2002; Charles and Shuichi 2003). In cogeneration system of sugar mills, bagasse is burnt to produce heat and steam for the mill functioning and electricity generation (Ensinas et al. 2006).
- Enzymatic hydrolysis of sugarcane bagasse can result in glucose, xylose, ethanol, and methane production (Bommarius et al. 2008; Guilherme et al. 2015; Rezende et al. 2011).
- Sugarcane bagasse and molasses can also find applications in producing fungal invertase (β-fructofuranosidase), a key catalytic enzyme in food industry (Veana et al. 2014). This enzyme is used to prepare artificial sweeteners (Aranda et al. 2006; Ashokkumar et al. 2001). The fructosyltransferase activity of the enzyme helps synthesize fructo-oligosaccharide compounds that improve intestinal microflora and has health benefits (Khandekar et al. 2014; Linde et al. 2009).
- It is also used to make paper by virtue of its high cellulose content (Daud et al. 2007).
- It is also employed as animal feed as it contains sugar and fiber.
- Sugarcane bagasse ash may be partly used in ceramic floor tile due to high SiO_2 contents (85.5%); moreover, it can also find applications as a source of fertilizer (Faria 2011).

16.2 Bioethanol Production at Sugar Industries

Fossil fuels, although played a discrete role in industrialization of emerging economies, yet, they gave rise to environmental and economic concerns (Colombo et al. 2014; International Energy Agency [IEA] 2015; O'Sullivan and Sheffrin 2003). An increasing awareness regarding these issues inculcated engineering to new research areas to evade fossil-dependent economies to an endurable form of growth using renewable green energy sources (Colombo et al. 2014; National Academic Press [NRC] 2000). Traditionally, sugar mills can produce bioethanol for fuel blending and generate their own energy from bagasse and other sugarcane feedstocks for their operations.

Biofuels like ethanol and biodiesel are among the rapidly developing sources of energy. Global production of biofuels amounted to 133 billion liters in 2015 distributing as 62% bioethanol and 24% biodiesel (Kummamuro 2016). Global bioethanol production tripled from its 2000 level and reached 52 billion liters in 2007 and to 99 billion liters in 2013. Brazilian ethanol from sugarcane and American ethanol from maize are by far leading the ethanol production. In 2015 the United States' corn and Brazil's sugarcane accounted for about 87% of the world ethanol production (Kummamuro 2016).

Bioethanol is a high-octane fuel which is used mainly as a gasoline stabilizer and replacement of fuel additive methyl tertiary butyl ether (MTBE)—an environmental inimical and contaminant to groundwater. High ethanol blends also help to control surge in prices for petroleum-based fuels (United Nations Development Programme [UNDP] 2009). Moreover, GHG release can be alleviated by increase in ethanol production with the hydrolysis of lignocellulosic cane residues (surplus bagasse and trash) in addition to molasses and sucrose (Seabra and Macedo 2011; Seabra et al. 2014).

Bioethanol originates from carbohydrates like sugar, starch, and celluloses by fermenting them with yeast or other microorganisms. The theoretical yield of ethanol is 617 L ton^{-1} of sucrose (Rein 2004) with the possible real recovery of 533.7 L ton^{-1} of sucrose (Table 16.1). Similarly, one ton of molasses yields about 263 L of ethanol. About 27.8 billion liters of bioethanol have been blended with fossil fuels in Brazil for motor vehicles, accounting for 26.3% of total Brazilian fuel consumption in 2017 (Barros and Berk 2018). Ethanol production from sugarcane is economically viable in many of the sugarcane-producing countries because of the drop in sugar support prices and advantages associated with the division of sugarcane production for multiple products. The cost of ethanol production in Brazil is in the range of US\$2.50 to 5.70 daL^{-1} (Galvao et al. 2016; Walter and Dolzan 2009). Likewise, other cane-producing countries could have multipurpose factories for economic advantages as well as for partial replacement of fossil fuels with the ethanol.

Table 16.1 Ethanol conversion per unit of different feedstocks (USDA 2006)

Commodity	Ethanol conversion factor (L ton^{-1} of feedstock)
Barley	243.4
Corn	371.7
Sugarcane[a]	73.8
Sugar beet[b]	93.9
Molasses[c]	262.7
Raw sugar	512.5
Refined sugar	533.7
Grain sorghum	402.4
Wheat	389.1

[a] Based on 2003–2005 United States (US) raw sugar recovery rate of 12.26% and sucrose recovery from cane molasses at 1.89% by sugarcane weight

[b] Based on 2003–2005 US average refined sugar recovery rate of 15.5% by sugar beet weight and sucrose recovery from beet molasses at 1.81% by sugar beet weight

[c] Based on average sucrose recovery of 49.2% of cane molasses (Rein 2004)

16.2.1 Sugarcane as an Ethanol Source

Feedstocks for ethanol production comprise C_3 plants (wheat, barley, and sugar beet) and C_4 plants (sugarcane and corn):

1. Corn: Two processes are used in the United States to obtain ethanol from corn, i.e., wet and dry milling process. Dry milling covers about 79% of ethanol production, while wet milling refers to only 21% of ethanol synthesis. Corn needs pre-hydrolysis before fermentation (United States Department of Agriculture [USDA] 2006).
2. Sugar beet: Processing plants convert sugar beet into refined sugar and release molasses and beet pulp as by-products leading to ethanol production.
3. Sugarcane: Sugar mills convert sugarcane to raw and refined sugars along with molasses and bagasse. Molasses and sugars are used in the production of alcohol for beverages and fuel. Raw or refined sugars and molasses do not need pre-hydrolysis before fermentation as in the case of corn or other feedstocks.
4. Other feedstocks: Wheat, barley, and grain sorghum. The conversion efficiency of different feedstocks is listed in Table 16.1.
5. Cellulosic biomass: Sugarcane bagasse and trash, wheat straw, wheat husk, rice straw, etc. need pretreatments before alcoholic fermentation.

The ethanol yields of corn are lower than sugarcane and sugar beet. In sugarcane or sugar beet allied fermentation units, the sugarcane or sugar beet extract, sugars, and molasses are used to make ethanol. Almost 25 L of sugarcane molasses is produced with each 100 kg raw sugar production (USDA 2006). Using raw sugar recovery factor of 12.26% and molasses sucrose contents of 49.2% for a sugarcane factory, one ton of sugarcane yields about 126.8 kg sucrose enabling to produce 73.8 L ethanol (Table 16.1). Sugar recovery is somewhat more in sugar beet compared against that of the sugarcane. Relatively more beet sugar recovery (15.5%)

and molasses sucrose contents of 50% (molasses are 4% by weight of sugar beet) enable it to produce 93.9 L ethanol ton^{-1} of sugar beet. One ton of molasses would yield 262.7 L of ethanol while raw and refined sugars would produce 512.5 and 533.7 L ethanol, respectively. However, per hectare yield of sugarcane is extremely high as compared to sugar beet making it an ideal candidate for finding applications as a biofuels source to meet huge demands of the same.

16.2.2 Technological Aspects of Ethanol Production from Sugarcane

The prerequisites for ethanol production are:

- Uninterrupted accessibility of feedstock in larger quantities
- Escalation in production efficiency to make the process sparingly suitable
- Environmentally and instrumentally safe process

Steps involved in bioethanol production process are feedstock collection, feedstock preparation, washing/separation/hydrolysis, fermentation using yeast, distillation, dehydration, and removal of solid residues and CO_2 (Barriga 2003). Major determining step, however, is fermentation that involves microbial activities under specific conditions. Different species of bacteria and yeasts responsible for alcoholic fermentation have been investigated by a number of workers (Behera et al. 2012; Bangrak et al. 2011; Cazetta et al. 2007; Gasmalla et al. 2012; Morias et al. 2007). Current industrial ethanol fermentation is largely achieved through *Saccharomyces cerevisiae* that is tolerant to low pH and high ethanol concentrations; moreover, *Zymomonas mobilis* bacterium is also employed for ethanol production from glucose and sucrose (Yang et al. 2007).

Molasses appears to be the cheapest source of ethanol production that can be purified to make absolute and rectified spirit (Sam 2012). The chemicals required during fermentation process are sulfuric acid, phosphoric acid, and ammonium sulfate. The important chemical reactions incurred in the process are:

$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6$ yeast/enzyme invertase (Sam 2012)
$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$ yeast/enzyme zymase (Morias et al. 2007)
$2C_6H_{12}O_6 + H_2O \rightarrow ROH + RCHO$ (high molecular weight alcohols and aldehydes produced as side reaction, Sam 2012)

Molasses from sugar industries are stored in large-volume storage tanks for continuous operation of distilleries. Molasses, at first, are diluted with water to the level of 15–20% sugar concentration (Gasmalla et al. 2012). Then acids are added to adjust pH between 4.5 and 5 for the growth of yeast to break up the sucrose in the diluter equipment. A yeast culture tank containing ammonium and magnesium phosphate is used for yeast propagation that produces invertase and zymase type of catalytic enzymes. A schematic diagram is given for molasses fermentation in Fig. 16.2.

The treated molasses and the yeast are then supplied to the fermentation chamber at a ratio of about 20 to 1 and powered with heating coils or jackets to maintain

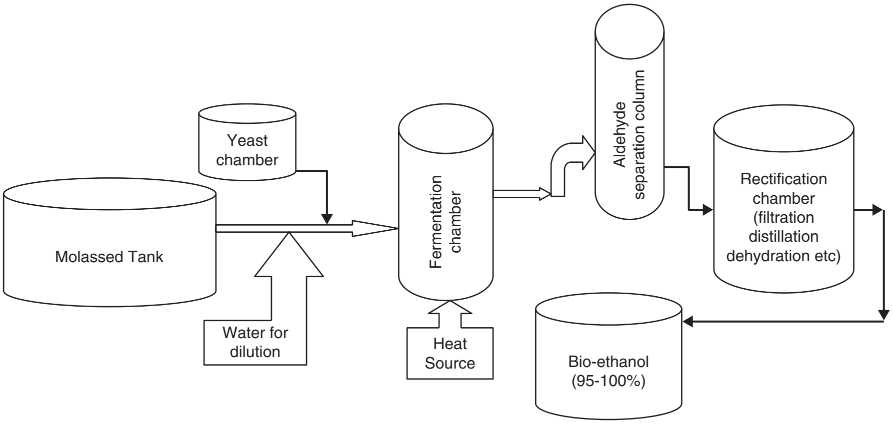

Fig. 16.2 Process of ethanol production by molasses fermentation (Sam 2012)

temperature of 20–35 °C in the tanks. The fermentation process is carried out for 30–70 hours considering temperature, sugar concentration, and yeast count. During this process carbon dioxide is also produced by microbial activity. Henceforth the mixture is strained to remove solid and slurry material leaving alcohol and water behind; where alcohol concentration is around 10% that is fed to the distillation unit for refining.

Distillation and dehydration of alcohol mixture are carried out in distillation unit for purifying the ethanol. In distillation, ethanol and water are separated by considering their different boiling points. The series of distillations lead to 95% pure ethanol leaving behind some intermolecular spaced water in it. This intermolecular spaced water is escaped through dehydration, which is done either by azeotropic distillation using entrainer (benzene or cyclohexane) or by molecular sieves like zeolite with pore size under 0.4 nm—preferably 0.3 nm (Angstrom)—that trap 0.44 nm ethanol molecules and drain out water molecules having 0.28 nm diameter (Carmo and Gubulin 1997; Díaz et al. 2010).

16.2.3 Ethanol Production from Lignocellulosic Biomass: Bagasse, Pressmud, Trash, and Others

Apart from sugar, and first-generation ethanol, sugarcane is also a great source of lignocellulosic biomass which can be subjected to second-generation ethanol production. High biomass yields of sugarcane make it an excellent source of the same in this regard. Sugarcane trash, straw, and bagasse, all can be employed for alcoholic fermentation. Bagasse, the fibrous residue obtained after extracting the juice from sugarcane during the sugar production process, has great potential as substrate for second-generation ethanol as it is found in large quantities in the sugarcane-growing countries. Currently, bagasse is either stored in a stockpile or burned for cogeneration, hence the growing interest in developing technologies for its conversion not only to ethanol but other petroleum-based chemicals like polymers, resins, and organic acids.

Plant cell wall is composed of cellulose, hemicellulose, and lignin. Sugar or molasses fermentation involves plain pretreatment steps as they do not need saccharification. Contrarily, lignocellulosic biomass needs another pretreatment to solubilize cellulose. There are about 73.9 million tons of dry wasted crops and about 1.5 billion tons of dry lignocellulosic biomass that need proper utilization annually (Kim and Dale 2005). The lignocellulosic biomass fermentation is of significance regarding food vs. fuel issues as these feedstocks does not impact sugar production. The pretreatment for lignocellulosic biomass is prerequisite to hydrolyze and delignify the material for enzymatic effectiveness (Gould 1985). Such pretreatments include acid treatment with sulfuric acid (Esteghlalian et al. 1997), alkaline treatment by aqueous ammonia to take out 70–85% lignin and solubilize 40–60% hemicelluloses (Kim et al. 2003) without affecting other components (McMillan 1997), and thermo-acid treatment. The steam (hydrothermal) treatment (150–230 °C) breaks down the plant cell wall through hydrolysis to ease enzymatic biodegradations (Boussarsar et al. 2009; Shaibani et al. 2011; Stenberg et al. 1998). Delignification in sugarcane bagasse with dilute acid-sodium hydroxide yields 96 and 85% of hemicellulose and lignin fractions, respectively, increasing the cellulose conversion from 22.0% in untreated to 72.4% in treated bagasse (Rezende et al. 2011).

The pretreatment of cellulosic biomass facilitates enzymatic hydrolysis to produce glucose and xylose as depicted in Table 16.2 (Guilherme et al. 2015; Rezende et al. 2011; Shaibani et al. 2011), followed by fermentation for ethanol (Bommarius et al. 2008; Sun and Cheng 2002). Another method called immobilized cell system provides high density in the reactor that allows elevated flow rate to squeeze the process time. It works through attachment of yeast to a surface, entrapment in a porous matrix, and containment behind an obstacle and self-agitation (Verbelen et al. 2006). The entrapped yeast in porous matrix produces 11.5 times more ethanol than the free yeast cells (Nigam 2000).

Cellulose conversion technologies are just emerging, technically unsound yet and commercially immature, hence will only allow utilization of lignocellulosic parts of sugarcane after having a dynamic research in the area (Rezende et al. 2011).

16.2.3.1 Biomass Composition

Lignocellulosic biomass of cane crop, such as sugarcane bagasse and energy cane bagasse, are composed of cellulose (30–43% DW, a linear polymer of glucose units linked by a β-glucoside bond), hemicellulose (23–27% DW, a branched heteropolymer with xylan as the major constituent, which is a heteropolysaccharide with varying proportions of xylose, arabinose, galactose, and mannose and with other groups such as glucuronic acid or acetic acid attached to its backbone), lignin (25–27% DW, a complex, heterogeneous, and branched polymer of phenolic and enolic compounds), and other components, e.g., protein, ash, and extractives (Aita and Kim 2011; Oladi and Aita 2017; Oladi and Aita 2018). The association and complexity of the lignin-polysaccharides complex make enzymatic accessibility a challenge,

Table 16.2 Composition of pretreated bagasse and cellulose conversion by enzymatic hydrolysis

					Enzymatic hydrolysis (cellulase complex and β-glucosidase)		
Pretreatment	Cellulose(%)	Hemicellulose (%)	Lignin (%)	Conversion (%)	Glucose (g L^{-1})	Cellobiose (g L^{-1})	Xylose (g L^{-1})
None (raw material)	38.59	27.89	17.79	–	–	–	–
Acid + alkaline	65.03	10.95	8.12	49.50	20.89	1.04	2.39
Hydrothermal + alkaline	62.14	11.52	7.87	35.65	15.22	0.58	1.26
Alkaline alone	47.21	29.29	4.31	82.28	25.79	10.29	15.58
Hydrogen peroxide alone	53.85	22.02	7.99	85.15	33.87	3.76	3.73

Source: Guilherme et al. (2015)

which is the main obstacle in the bioconversion of fermentable sugars to second-generation ethanol (Aita and Kim 2011).

16.2.3.2 Biomass Pretreatment

Once the biomass is harvested, collected, and transported to the processing plant, the next step is to convert the biomass into ethanol. This can be accomplished by depolymerizing the lignin-polysaccharides matrix into their respective monomers. US DOE has reported that pretreatment is the second largest production cost following the cost of feedstock and has predicted that this would still be the case in future commercial-scale facilities (Humbirt and Aden 2008). The high costs are related to the need for reactors capable of operating under high temperatures and pressures, the use of corrosive catalysts and the need for their recovery (Stephen et al. 2012). Several technologies have been developed for the conversion of lignocellulosic biomass into ethanol and are grouped into two categories, biochemical and thermochemical conversion technologies. In biochemical conversion, the cellulose and hemicellulose present in the lignocellulosic biomass are broken down to their monomeric sugars (glucose, xylose, arabinose, mannose, and galactose) and then fermented into ethanol. The lignin which cannot be fermented into ethanol is fed into a boiler for energy production. In thermochemical conversion, the lignocellulosic biomass is gasified to produce syngas (a mixture of carbon monoxide, hydrogen, carbon dioxide, methane, and nitrogen) and then fermented or catalytically converted to ethanol.

16.2.3.3 Biochemical Conversion

The overall target of biochemical conversion is to provide enzymes better accessibility to the polymeric sugars, thus enhancing the bio-digestibility of lignocellulosic biomass. The biochemical conversion of bagasse to ethanol can be accomplished by the following steps: pretreatment, detoxification, hydrolysis, fermentation, and distillation. A successful biochemical conversion method should improve enzymatic accessibility by having minimal fermentable sugar losses, reducing the formation of toxic or inhibitory compounds (i.e., organic acids, furan derivatives, phenolic compounds), generating minimum waste products, having low capital and energy costs, and being suitable for a wide range of lignocellulosic biomass materials (Sun and Cheng 2002). The toxic compounds generated from the degradation of cellulose, hemicellulose, and lignin during pretreatment have shown inhibitory effects on downstream processes (i.e., enzymatic hydrolysis, microbial fermentation) thus the need for their removal (Alvira et al. 2010). Biochemical conversion methods can be classified as physical (e.g., grinding, extrusion, irradiation), chemical (e.g., acid, alkaline, liquid hot water, ionic liquids), physicochemical (i.e., steam explosion, AFEX), biological, or a combination of these methods. Although dilute acid, alkaline, and steam pretreatments are the technologies most commonly used, a variety of biochemical pretreatments have been used for sugarcane and energy cane bagasse, each having inherent advantages and disadvantages (Table 16.3).

Table 16.3 Biochemical processes used for the pretreatment of sugarcane and energy cane bagasse

Pretreatment Process	Mode of Action	Advantages	Disadvantages
Physical	Milling, er indine, irradiation to reduce particle size	Reduces cellulose crystallinity	High power and energy consumption
		Increases surface area	
Chemical			
Liquid hot water	High temperature (>120 °C) and pressure (5 MPa)	Causes lignin degradation/ hemicellulose solubilization	Partial hemicellulose degradation
	1–80 min to remove hemicellulose	Most cellulose is preserved	Generation of inhibitory compounds
		Neutralization step is not needed	Detoxification is needed
		No chemicals corrosion resistant materials required	High energy investment and water demand
Acid	(e.g., sulfuric) concentrated (18–40% acid, 80 °C, 90 min) or dilute acid 1.80–10%, 100–120 °C, 40–120 min) to solubilize hemicelluloses/lignin	High sugar yields	High cost
		Hydrolyze hemicelluloses	Acids need tobe recovered
			Equipment corrosion problems
			Formation of inhibitory compounds
			Neutralization step is needed
Alkaline	(e.g., sodium hydroxide, ammonium hydroxide) disrupts ester and glycosidic chains causing cellulose swelling, lignin degradation, partial decrystallization and solubilization of hemicellulose (53–160 °C, 1–4 h)	Increases accessible surface area	Salts are formed and incorporated into biomass
		Removes lignin and hemicellulose	Requires long residence times
		Decreases cellulose cristallini tv	
		Requires low temperatures	
Ionic liquids	Salts with a small anion and a large organic cation that dissolves the cellulose (60–140 °C, 5–360 min)	No inhibitor production	High cost
		Low sugar degradation	Washing required prior to reuse of ionic liquids
		Environmental friendly	

(continued)

Table 16.3 (continued)

Pretreatment Process	Mode of Action	Advantages	Disadvantages
Organesolv	(e.g., ethanol, methanol, acetone, etc.) to hydrolyze hemicellulose and lignin (150–200 °C, 30–90 min)	Hydrolyzes lignin and hemicellulose	High cost
		Recovery·of relatively pure ligin as byproduct	Cataysts need to be drained and recycled
			Safety, high solvent volatility
Physicochemical			
AFEX	Liquid ammonia treatment followed by sudden pressure release to disrupt biomass and decrystallize cellulose (60–100 °C, 30–60 min, 1.7–2 Mpa)	Increases accessible surface area	No efficient in high-lignin content biomass
		Removes lignin and hemicellulose	Cost of ammonia
		No inhibitors produced	
Steam explosion	Biomass exposed to hot steam and high pressure followed by sudden release of pressure to disrupt cell wall structure and hemicellulose (160–260 °C, 15 min, 0.6–4.3 MPa)	High sugar yield	Incomplete delignification
		Cost effective	Partial hemicellulose degradation
		Lower environmental impact	Generation of inhibitory compounds
Biological	Microorganisms (e.g. white-rot, brown-rot fungi) produce lignin peroxides and laccase that causes lignin degradation	Low energy requirements	Slow rate of hydrolysis
		Degrades lignin and hemicellulose	Less of sugars as utilized by microorganisms

Aita and Kim (2011), Fatma et al. (2018), Rastogi and Shrivastava (2017)

16.2.3.4 Detoxification

Hydrolysates that result from the biochemical pretreatment of lignocellulosic biomass may contain by-products other than sugars, including organic acids, furans, and phenolic compounds. These inhibitory compounds can negatively affect downstream processes such as enzymatic hydrolysis and fermentation. The nature and concentration of the generated inhibitory compounds are directly related to pretreatment conditions and biomass composition (Jönsson and Martín 2016).

Detoxification methods can be categorized into physical (i.e., evaporation), physicochemical (i.e., liquid-liquid extraction, ion-exchange resins, overliming, activated carbon, flocculation), microbial (i.e., *Issatchenkia* spp., *Trichoderma* spp.), and enzymatic (i.e., laccases, peroxides) (Canilha et al. 2012; Deng et al. 2018; Deng and Aita 2018; Palmqvist and Hahn-Hägerdal 2000). There might be a need to combine several detoxification strategies to reach the target concentration level for inhibitors as each of these strategies have some inherent shortcomings (Ranjan et al. 2009). Sugar losses while applying detoxification strategies to pretreated biomass hydrolysates should be negligible (Mussatto and Roberto 2004). According to Sivers et al. (1994), the cost of a hydrolysate detoxification process can be up to 22% of the total cost of ethanol production.

16.2.3.5 Hydrolysis Technologies

Hydrolysis is the process that comes after biochemical pretreatment and detoxification, and it involves breaking down the polymeric sugars into their monomeric forms. This process is often catalyzed by an acid or enzymes, and it is critical in the production of ethanol since the quality of the hydrolysate will affect the subsequent fermentation process. This strategy not only offers the possibility of substrate specificity but reduces processing time from weeks to hours without the need of carbohydrate consumption as seen with biological pretreatment methods (Moreno et al. 2015). Hydrolysis represents 25–30% of the operational costs (Valdivia et al. 2016). Acid hydrolysis involves the use of dilute or concentrated acids, and it is only applicable to lignocellulosic biomass that has been pretreated with dilute acid technologies. Dilute acid (0.4%) at 215 °C with 3 min residence time are employed for converting cellulose to glucose (Hamelinck et al. 2005). A drawback is the recovery of the acid in high yields. However, two US companies, BlueFire Renewables and Virdia, claim to have overcome this challenge at pilot scales using concentrated sulfuric acid (Arkenol process) and hydrochloric acid (cold acid solvent extraction process), respectively (Hayes 2016).

Compared to acid hydrolysis processes, enzymatic hydrolysis is the preferred method due to its effectiveness, mild pH (4–5) and temperature (45–55 °C), and non-corrosive properties (Aditiya et al. 2016; Mohapatra et al. 2017). The highest glucose yields that can be achieved with untreated biomass using excessive amounts of enzymes will not exceed 20% (Mosier et al. 2005). Despite the improvement in the digestibility of lignocellulosic material after pretreatment, the complex structure of lignocellulosic biomass still requires the use of enzymes, e.g., cellulase, to yield maximum carbohydrate conversions. Enzymatic hydrolysis strongly depends on microbial species, biomass chemical composition, pretreatment method, and enzyme mode of action (Pothiraj et al. 2014). Enzyme loadings, the use of accessory enzymes (xylanase, feruloyl esterase, pectinase, laccase), and the presence of inhibitory compounds (phenolic compounds, furan derivatives, organic acids) can also affect carbohydrate conversion yields during enzymatic hydrolysis (Bussamra et al. 2015). Enzymes used for lignocellulosic biomass hydrolysis can be produced by both bacteria such as *Clostridium cellulovorans* and fungi such as *Trichoderma reesei*, *Aspergillus niger*, and *Pycnoporus* spp. (Mohapatra et al. 2017; Talebnia et al. 2010).

The availability of cost-effective commercial enzymes to produce second-generation ethanol remains a challenge, and innovative bioprocesses to produce a new generation of enzymes are still needed. Current commercially available enzymes include Accellerase®1500 (DuPont), a mixture of exoglucanase, endoglucanase, xylanase, and β-glucosidase. Accellerase® XP (DuPont), Accellerase® XC (DuPont), and Accellerase® BG (DuPont) are accessory enzymes with cellulose and hemicellulose activities which can be used in combination with Accellerase®1500. Cellic® CTec2 (Novozymes®) and HTec2 (Novozymes®) contain cellulase, β-glucosidase, xylanase, and endoxylanase, respectively. Celluclast® 1.5 L (Novozymes®) has cellulase activity.

16.2.3.6 Fermentation

The hexose (mostly glucose) and pentose (mostly xylose) sugars released during the hydrolysis of bagasse or lignocellulosic biomass are subsequently converted into ethanol via anaerobic or aerobic fermentation by a variety of microorganisms. The yeast *Saccharomyces cerevisiae* has been historically used for the fermentation of glucose into ethanol. However, this organism cannot ferment pentose sugars, a significant limitation since pentose sugars account for at least 25% of the mass balance of many lignocellulosic biomass materials (Hayes and Hayes 2009). For lignocellulosic ethanol to be economical, fermentation of both hexose and pentose sugars must result in high yields. Theoretically, each kg of glucose and xylose can produce 0.45 kg carbon dioxide and 0.51 kg ethanol (Hamelinck et al. 2005). A way to overcome this obstacle is to use microbial genetic engineering tools. Common targeted organisms include *Zymomonas mobilis*, *Escherichia coli*, and *Saccharomyces cerevisiae* (Lawford and Rousseau 1991). However, in some cases, the genetically modified strains of these conventional fermentative microorganisms are not sufficiently robust to function in large-scale industrial environments (Hahn-Hagerdal et al. 2007). Several integrated technologies have been proposed to increase the efficacy of ethanol production such as separate hydrolysis and fermentation (SHF), simultaneous saccharification and fermentation (SSF), simultaneous saccharification and cofermentation (SSCF), and consolidated bioprocessing (CBP).

Separate Hydrolysis and Fermentation (SHF)

SHF is a classic two-step process configuration where lignocellulosic biomass hydrolysis and fermentation are carried out separately thus allowing each step to be performed at its optimal operating conditions (pH and temperature) and at relatively shorter times (Sarris and Papanikolaou 2016). Substrate concentration at 10% (w/w) solid loadings are defined as the most adequate considering arising mixing difficulties and the accumulation of sugars which inhibit enzyme activity (end-product inhibition), thus ultimately affecting ethanol yields (Jambo et al. 2016; Sánchez and Cardona 2008). The following ethanol concentrations have been reported with steam pretreated sugarcane bagasse (26 g L^{-1}), liquid hot water pretreated sugarcane bagasse (25 g L^{-1}), phosphoric acid pretreated sugarcane bagasse (25 g L^{-1}), sulfuric acid pretreated sugarcane bagasse (20 g L^{-1}), dilute ammonia pretreated sugarcane bagasse (20 g L^{-1}) or energy cane bagasse (23 g L^{-1}), and ionic liquid (1-ethyl-3-methylimidazolium acetate) pretreated energy cane bagasse (18 g L^{-1}) (Aita et al. 2011; Bezerra and Ragauskas 2016; Cao and Aita 2013; Neves et al. 2016; Qiu et al. 2014; Torres da Silva et al. 2016).

Simultaneous Saccharification and Fermentation (SSF)

Hydrolysis and fermentation are combined in a single reactor so that glucose is fermented (separately of pentoses) or cofermented to ethanol as soon as the sugars are released by enzymes, thus overcoming the accumulation of hydrolytic end products (glucose and cellobiose) which are inhibitory to cellulolytic enzymes (Ferreira et al. 2010). Benefits of this process include ease of operation, low equipment requirement than SHF, and the presence of ethanol in the medium which reduces the contamination risk of external microflora (Vohra et al. 2014). SSF also allows for high solid loadings (30% w/w) (Mohapatra et al. 2017). Major drawbacks include difficulty in optimizing process parameters for both enzymes and microorganisms, such as incompatible hydrolysis (45–50 °C) and fermentation (28–30 °C) temperatures, ethanol toxicity to microorganisms, and enzyme inhibition by ethanol (Rastogi and Shrivastava 2017). The use of protein engineering to lower the optimum temperatures of enzymes would be a challenge so the alternative is to use thermotolerant strains that could grow well and produce ethanol at higher temperatures (Hasunuma and Kondo 2012). SSF still requires the microorganism to be grown in a separate reactor where 9% of the sugars from hydrolysates are used to grow cellular mass (Hayes 2016). A study conducted with 10% sugarcane bagasse pretreated with sodium hydroxide/hydrogen peroxide combination resulted in 25 g L^{-1} ethanol using *Kluyveromyces maxianus* DW08 as the ethanol-fermenting yeast (Cheng et al. 2008). Other ethanol concentrations reported include liquid hot water pretreated sugarcane bagasse (19 g L^{-1}), sulfuric acid pretreated sugarcane bagasse (18 g L^{-1}), and phosphoric acid pretreated sugarcane bagasse (17 g L^{-1}) (Bezerra and Ragauskas 2016; Neves et al. 2016; Torres da Silva et al. 2016).

Simultaneous Saccharification and Cofermentation (SSCF)

A simplified process where the pretreated lignocellulosic biomass material is combined with different enzymes and microorganisms in the same reactor with the purpose of hydrolyzing both the hexose and pentose sugars and fermenting them into ethanol (Lynd 1996). However, SSCF has been slow to develop commercially because optimal conditions required for hydrolysis and fermentation are different, and improved microbial strains are needed for the cofermentation of all sugars (Chandrakant and Bisaria 1998; Koppram et al. 2013). *Saccharomyces cerevisiae* TMB3400, a xylose-fermenting recombinant strain, and *P. stipitis* CBS6054, a naturally xylose-fermenting strain, were compared in SSF of non-detoxified hydrolysate from steam pretreated sugarcane bagasse previously impregnated with sulfate (Rudolph et al. 2007). The highest ethanol concentration (26.7 g L^{-1}) was obtained with *S. cerevisiae* TMB3400, whereas *P. stipitis* CBS6054 resulted in 19.5 g L^{-1} under aerated conditions.

Consolidated Bioprocessing (CBP)

CBP represents the ultimate simplification of the enzymatic hydrolysis and microbial fermentation process where a fungus (i.e., *Trichoderma reesei*, *Fusarium oxysporum*, *Neurospora crassa*, *Aspergillus* spp., *Rhizopus* spp., *Paecilomyces* spp.), a yeast (i.e., *Candida shehatae*, *Pachysolen tannophilus*, *Saccharomyces cerevisiae*, *Pichia stipitis*), or a bacterium (i.e., *Clostridium thermocellum*, *Escherichia coli*, *Klebsiella oxytoca*, *Zymomonas mobilis*) is capable of both hydrolyzing the polysaccharides and fermenting them into ethanol in a single reactor (Aditiya et al. 2016; Taherzadeh et al. 2000). CBP has the potential to offer the lowest production cost for ethanol but current limitations include low yields and long periods for fermentation by up to 12 days (Koutinas et al. 2014). Thermophilic microorganisms, e.g., *Clostridium* spp., have an advantage over conventional yeast in that they can withstand high temperatures, but a major obstacle for their industrial application is their low ethanol tolerance (<2% v/v) (Rastogi and Shrivastava 2017). No microorganisms or compatible combinations of microorganisms are available that exhibit the whole combination of features required for the development of CBP (Kazi et al. 2010). The success of this approach relies heavily on genetic and metabolic engineering for the development of CBP-enabling microorganisms for the industrial production of second-generation ethanol.

16.2.3.7 Thermochemical Pretreatment

Gasification involves the thermal (600–1000 °C) decomposition of both lignin and polysaccharides into a syngas in the presence of an oxidizing agent (oxygen or steam) (Kumar et al. 2009). Syngas is mainly a mixture of carbon monoxide, carbon dioxide, hydrogen, water, and short-chain hydrocarbons which can then be converted into fuels and chemicals (e.g., ethanol, methanol, higher alcohols, gasoline) by either fermentative microorganisms or metal catalysts (Sutton et al. 2001). The quality of syngas depends on the type of biomass (i.e., chemical composition, moisture, particle size, tar content), design of the gasifier (i.e., updraft or downdraft fixed bed reactors, bubbling or recirculating fluidized bed reactors), and operational conditions of the reactor (Kennes et al. 2016). A challenge of current gasification technology is the presence of large amounts of tar (a mixture of unconverted organic materials and ash) in the syngas, which results in plugging of downstream equipment (compressors and gas engines) (Watson et al. 2018). Other limitations facing this technology include separation of gaseous products and the poisoning of catalysts by gasification products (hydrogen sulfide, thiophene, carbonyl sulfide) (Kochermann et al. 2015; Yin et al. 2016).

Anaerobic bacteria (i.e., *Clostridium* spp.) can ferment syngas into ethanol; however, the composition of syngas should be optimized so that it has reduced impurities including tar, ash, nitrogen oxides, and hydrogen sulfide and it mainly contains carbon monoxide, carbon dioxide, and hydrogen (Brown 2005). Advantages of the biological route over the use of catalysts include the use of lower processing temperatures and pressures, and higher ethanol yields, thus reducing the energy and capital cost of conversion (Farzad et al. 2016). Limitations involve providing optimum growth conditions (levels of nutrients and impurities) for microorganisms and microbial sensitivity to both impurities and high concentrations of end products (Mohammadi et al. 2011). In catalyst-based ethanol production, syngas is mixed with water and methanol to improve yields of higher alcohols, and the mixture is passed through a catalyst to obtain not just ethanol but methanol, higher alcohols, and other hydrocarbon products (Dwivedi et al. 2009). Natural catalysts (dolomite, hematite, trona) and transition metal catalysts (Ni-Mg-Al, Ni, NiO) are preferred due to their ease of recovery at the end of gasification (Guan et al. 2009; Wu et al. 2006). Inexpensive, large-scale biomass gasifiers have yet to be demonstrated as well as the successful commercial-scale production of fuels from syngas.

16.2.3.8 Distillation

One of the main issues associated with ethanol production from lignocellulosic biomass (biochemical and thermochemical conversion platforms) relies on the cost-effective recovery of ethanol from the hydrolysates or fermentation broths. Ethanol recovery through common distillation methods is not technically challenging but it requires significant amounts of energy to yield concentrations of up to 85 wt% ethanol (Huang et al. 2008). The energy required to separate ethanol from water by distillation methods amounts to 10% of the energetic content of the recovered ethanol, with an exponential increase for ethanol concentrations below 10% (Vane 2008). Only anhydrous ethanol (>99 wt% ethanol) can be blended with gasoline and be used in conventional gasoline-burning engines. Ethanol and water form an azeotrope at 95 wt% ethanol thus making it impossible to recover pure ethanol through simple distillation; hence, the need for a special dehydration process to recover anhydrous ethanol (Haelssig et al. 2012). The most commonly used techniques for ethanol dehydration include adsorption distillation, azeotropic distillation, chemical dehydration, diffusion distillation, extractive distillation, and membrane distillation (Aditiya et al. 2016). Liquid (water, unutilized fermentable sugars, process chemicals) and solid (mostly lignin) wastes are generated at the end of the ethanol process and are collectively known as stillage, which can neither be sent to the sewer system nor be discharged into a water body or soil (Sheehan and Greenfield 1980). Several stillage utilization techniques have been developed to recover energy (heat and power generation) and process water, as well as its potential use as animal feed, fertilizers, and road-building materials (Baral et al. 2017).

16.2.4 Stress Management During Fermentation

The stress factors for yeast which affect fermentation efficiency include concentrations of sugar and ethanol, bacterial infection, temperature, nutrient levels, and mycotoxins (Bleoanca and Bahrim 2013). Yeast can normally tolerate one stress at a time to some extent. However, simultaneous two or more stresses appear to be deleterious for yeast. Lactic and acetic acids are the spin-off produced by the contaminating bacteria (lactobacilli, acetobacter, and gluconobacter), which may hinder the fermentation process at higher concentrations.

Before rectification, some aldehydes produced in the process of fermentation are detached at aldehyde column. The stream in columns accumulates aldehydes at the top, fuselol-containing ethanol in the middle, and water at the bottom. The middle stream is fed to rectification column to relent 95% pure ethanol.

16.2.5 Uses of Ethanol as Biofuel

- Gasoline is blended with ethanol for petrol engine vehicles for environmental benefits. Routine fuel additives like tetraethyl lead is environmentally unsafe, MTBE is water pollutant while toluene and benzene are also deleterious to health. Ethanol, due to structural oxygen, lessens the release of damaging GHGs, like unburnt hydrocarbons and carbon monoxide.
- Gasoline can be blended with anhydrous ethanol from 100 to 5% or less. In Brazil the flex-fuel vehicles (FFV) can use all the blends of ethanol. In countries, like Sweden, a maximum of 85% ethanol blend (E85) is used while in some countries E10 is used.
- Ethanol is also used to make ethyl tertiary butyl ether (ETBE) retaining 44% ethanol, an oxygenated octane used as gasoline blend.
- Diesel engines are also being tested for ethanol use.

16.2.6 Cost of Ethanol Production

The cost of first-generation ethanol production using different feedstocks is given in Fig. 16.3. The cost estimates are based only on estimated costs of feedstock, sugarcane market prices, and processing cost but exclude capital and transportation costs. The data indicates that cost of production varies with change in feedstock. The total cost of converting sugarcane into ethanol in Brazil appears the lowest as it has been estimated approximately US\$2.14 daL^{-1} (per decaliter), while maximum cost incurred on refined sugar conversion into ethanol is in the United States (US\$10.49 daL^{-1}).

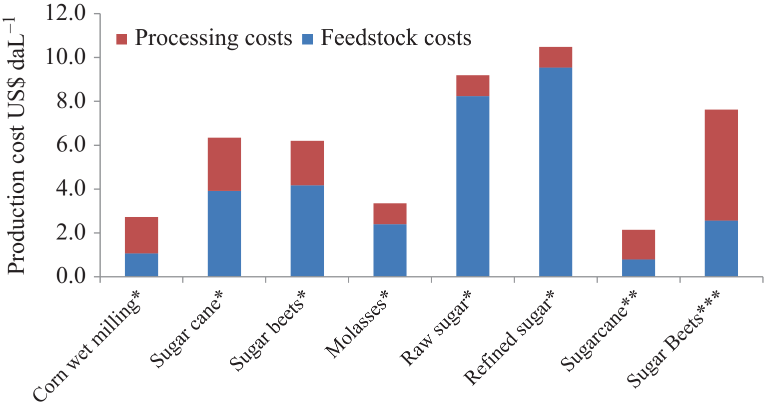

Fig. 16.3 Estimated ethanol production cost with different feed stocoks in different countries ∗USA, ∗∗Brazil, ∗∗∗E.U. (USDA 2006)

Some feedstocks are cheaper than the processing costs while the others are costly. Hence refine and raw sugars are dearer feedstocks compared to sugarcane, corn, and molasses feedstocks. The cost of converting sugar beets into ethanol was estimated at US\$5.07 daL^{-1} in the European Union (EU) that is the maximum cost among all the feedstocks. Molasses obtained from sugarcane or sugar beets as well as corn appear to be cost-competitive feedstock for ethanol production. Hence, different feedstocks have variable cost-effectiveness for ethanol production in different countries.

16.3 Bioelectricity Production at Sugar Mills Through Cogeneration

Cogeneration, meaning a joint heat and power production, is the concurrent creation of electricity, heat, and/or cooling with a single source of fuel at or near the sink. The most common fuels for cogeneration are natural gas, coal, plant materials (bagasse, rice husk, sugarcane trash, etc.), and gas from sludge or landfill material, liquid fuels, and renewable gases. Bagasse can be fired against coal, oil, or natural gas in a power plant to heat the boilers. The steam produced in the boilers can be used as a heat source for industrial (process heat) and domestic purposes. It can also be used in steam turbines for bioelectricity generation.

Bagasse cogeneration was initiated in Mauritius and Hawaii where about 26 and 10% of grid electricity were obtained from sugar mills in 1926–1927, respectively (International Sugar Organization [ISO] 2009). Cogeneration improved efficiency of the sugar plants to the tune of about 50% than separate electricity and power production. Traditional sugar mills generate their own heat and power but with low steam and temperature installation systems, whereas in high-efficiency cogeneration systems effective boilers permit spare electricity and economical heat basis for sugar processing. Traditional sugar mills generate 10–20 kW electrical energy per ton of cane for internal use, while modern sugar mills can have the efficient cogeneration systems of up to 115–120 kW per ton of cane (Kamate and Gangavati 2009).

Many countries have inadequate renewable energy resources and oil, gas, or coal reserves and hydropower supplies. Sugarcane bagasse signifying 30% of cane is commonly used incompetently to fulfil the factory's energy requirement for cane processing (Deepchand 2005), the competency of which can further be used to create surplus energy. In Mauritius, more than 90% sugar factories export 318 Gigawatt bagasse-made bioelectricity (40% of total) to the national grid in crushing season (Deepchand 2005). In the late 1980s, an annual increase in electricity use and demand in Mauritius was estimated to be 11 and 9.5%, respectively. Although Mauritius offers a successful demonstration of bagasse energy for other countries, it produces 60 kW of electricity per ton of cane that is less than 125 kW ton^{-1} made through Centrale Thermique de Belle Vue (CTBV) operated with 2 × 35 MW power plants at about 82 bars (Deepchand 2005).

Bagasse is burnt in furnaces to make steam for power production. Its value as a fuel depends mainly on its calorific value that is sequentially affected by its water content. A good milling process occurs at 45% bagasse moisture content, whereas the milling efficiency is reduced at 52% moisture. Mostly the boilers are designed to work at about 50% bagasse moisture content. Cogeneration with bagasse is among one of the most successful energy projects and is being established in several sugarcane-producing countries like Mauritius, the United States, India, Brazil, and Pakistan. Simultaneous heat and power generation from sugarcane bagasse presents a renewable energy alternative to uphold sustainable growth, boost sugar industry's income, and climate resilience through production of carbon-neutral electricity (De Rosa and Salvadori 2007).

16.3.1 Potential for Cogeneration in Sugarcane-Growing Countries

Table 16.4 shows Food and Agriculture Organization's statistics (FAOSTAT 2017) regarding the cogeneration potential of different countries. A significant amount of bioelectricity can be exported to the grids using two profitable technologies of steam pressures (44 and 82 bars) from the sugar mills having a minimum cane crushing of 200 to 300 ton per hour. It also emphasizes coupling of less capacity plants into larger units. There are about 107 countries producing sugarcane, whereas 85 countries are producing sugarcane more than 100,000 tons per year (FAOSTAT 2017). This table also summarizes the overall estimates for electricity production from sugarcane in the countries having annual production of 1.5 million tons of cane.

Table 16.4 Bagasse cogeneration capacity of different countries

Serial no.	Countries	Sugarcane production*	Estimated bagasse[a]	Cogeneration potential (GW)	
		"000" ton	"000" ton	at 44 bars[b]	at 82 bars[c]
1	Brazil	768678.4	215229.9	53807.5	84554.6
2	India	348448.0	97565.4	24391.4	38329.3
3	China	123059.7	34456.7	8614.2	13536.6
4	Thailand	87468.5	24491.2	6122.8	9621.5
5	Pakistan	65450.7	18326.2	4581.5	7199.6
6	Mexico	56446.8	15805.1	3951.3	6209.2
7	Colombia	36951.2	10346.3	2586.6	4064.6
8	Australia	34403.0	9632.8	2408.2	3784.3
9	Guatemala	33533.4	9389.4	2347.3	3688.7
10	United States of America	29926.2	8379.3	2094.8	3291.9
11	Indonesia	27158.8	7604.5	1901.1	2987.5
12	Philippines	22370.5	6263.8	1565.9	2460.8
13	Argentina	21990.8	6157.4	1539.4	2419.0
14	Cuba	18891.0	5289.5	1322.4	2078.0
15	Vietnam	16313.1	4567.7	1141.9	1794.4
16	Egypt	15760.4	4412.9	1103.2	1733.6
17	South Africa	15074.6	4220.9	1055.2	1658.2
18	Myanmar	10437.1	2922.4	730.6	1148.1
19	Peru	9832.5	2753.1	688.3	1081.6
20	Ecuador	8661.6	2425.3	606.3	952.8
21	IR Iran	7687.6	2152.5	538.1	845.6
22	El Salvador	7202.1	2016.6	504.1	792.2
23	Kenya	7094.6	1986.5	496.6	780.4
24	PS Bolivia	6910.8	1935.0	483.8	760.2
25	Nicaragua	6815.1	1908.2	477.1	749.7
26	Paraguay	6708.0	1878.2	469.6	737.9
27	Eswatini	5583.3	1563.3	390.8	614.2
28	Sudan	5525.1	1547.0	386.8	607.8
29	Honduras	5355.7	1499.6	374.9	589.1
30	Dominican Republic	4717.5	1320.9	330.2	518.9
31	Nepal	4346.8	1217.1	304.3	478.1
32	Zambia	4285.8	1200.0	300.0	471.4
33	Bangladesh	4207.6	1178.1	294.5	462.8
34	Costa Rica	4158.4	1164.3	291.1	457.4
35	Mauritius	3798.4	1063.6	265.9	417.8
36	Uganda	3723.0	1042.4	260.6	409.5
37	Zimbabwe	3483.0	975.2	243.8	383.1
38	BR Venezuela	3331.3	932.8	233.2	366.4

(continued)

Table 16.4 (continued)

Serial no.	Countries	Sugarcane production* “000” ton	Estimated bagasse[a] “000” ton	Cogeneration potential (GW) at 44 bars[b]	at 82 bars[c]
39	Madagascar	3005.6	841.6	210.4	330.6
40	UR Tanzania	2994.1	838.4	209.6	329.4
41	Malawi	2915.4	816.3	204.1	320.7
42	Mozambique	2761.5	773.2	193.3	303.8
43	Panama	2419.6	677.5	169.4	266.2
44	Guyana	2394.6	670.5	167.6	263.4
45	DR Congo	2191.3	613.6	153.4	241.0
46	PDR Lao	2019.0	565.3	141.3	222.1
47	Côte d’Ivoire (Ivory Coast)	1982.7	555.1	138.8	218.1
48	Réunion Island	1820.1	509.6	127.4	200.2
49	Japan	1574.0	440.7	110.2	173.1
50	Fiji	1556.7	435.9	109.0	171.2
51	Others	18599.5	5207.8	1302.0	2045.9
	Total			**132441.7**	**208122.7**

*Source: FAOSTAT (2017)

[a] Estimated at 280 kg per 1000 kg of cane having 50% moisture

[b] Based on 70 kW ton^{-1} of cane

[c] Based on 110 kW ton^{-1} of cane

16.3.2 Mechanism of Cogeneration

The sugar industry entails heat, electric, and mechanical energy to execute the milling process. Generally, the energy production in a factory is designed merely to furnish the sugar plant requirements where a range of machines and processes are taking place (Colombo et al. 2014).

Bagasse is fired in boiler house to generate heat and dispensing water steam. The boilers are large cylindrical chambers containing lower smaller part for burning of bagasse while the upper big part contains water in tubes that is in immediacy to the lower part for receiving heat (Fig. 16.4). Boilers are tied with backpressure or condensing-extraction steam turbines which deliver steam and electrical energy to the system (Khatiwada et al. 2012; Purohit and Michaelowa 2007). The steam is used either for mill processes or at high pressure for revolving turbines of electricity generation system. The general schematic view of bagasse-based power plant is described in Fig. 16.4. A sugar mill crushing ~2000 ton sugarcane per day is able to generate ~14,000 kW of bioelectricity daily including about 6000 kW for the

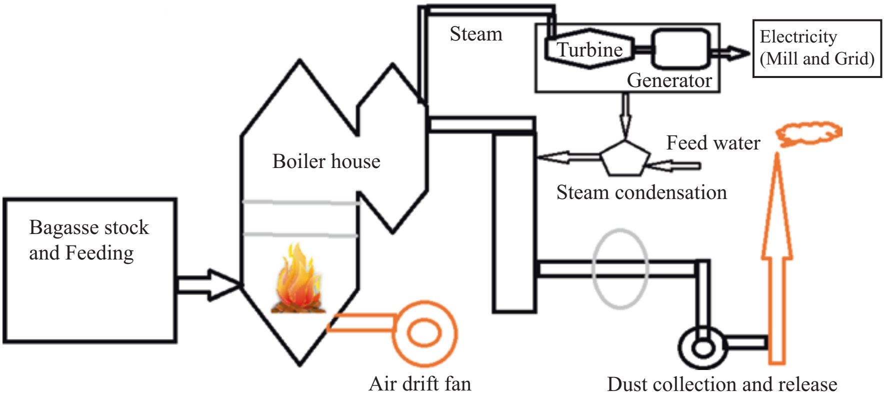

Fig. 16.4 Cogeneration system in sugar factory (Colombo et al. 2014; Ensinas et al. 2006)

industry's internal consumption. The major steps involved in production of electricity using bagasse as raw material are as follows:

(i) Bagasse storage in a moisture-free area of sugar mill.
(ii) A railing system transfers bagasse from storage to boilers.
(iii) The water in the tubes passes through economizers to make it warmer, and blazing of bagasse converts water into high-pressure steam that is partly used in sugar manufacturing process.
(iv) The high-pressure steam flows through controlled tubes to the turbines that rotate them to operate connected generators.
(v) Consequently, electricity is generated that is used in sugar industry while excess is provided to the grids.

In a sugar mill's cogeneration systems, the general parameters of concern have been reported by many researcher (Colombo et al. 2014; Ensinas et al. 2006; Hassuani et al. 2005), which include:

- Moisture in wet bagasse: 50%
- Wet bagasse low heat value (LHV): 7500 kJ kg^{-1}
- Bagasse mean LHV: 7984 kJ kg^{-1}
- Process mechanical energy demand: 16 kW per ton of cane
- Process electricity demand: 12 kW per ton of cane
- Boiler's thermal efficiency: 85%
- Steam turbines isentropic efficiency: 80%
- Boilers and turbines operate at 15–105 bar pressure with analogous temperature of 300–525 °C
- Pump isentropic efficiency: 80%
- Electric generator efficiency: 96%
- Mill electric engines efficiency: 89%

Table 16.5 Difference in surplus electricity generation with different setups in sugar mills

Country	Turbine system	Power (bar)	Temperature °C	Surplus electricity (kW ton^{-1} of sugarcane)
Brazil	BPST	22	300	0–10
Brazil	BPST	42	440	20.0
Brazil	BPST	67	480	40–60
India	CEST	67	495	90–120
India	CEST	87	515	130–140
Brazil	CEST (50% trash)	65	480	139.7
Brazil	CEST (50% trash)	105	525	158.0
Mauritius	–	45	440	60–90
Mauritius	–	82	525	110–130

Source: BNDES and CGEE (2008), Khatiwada et al. (2012), Rosillo-Calle et al. (2015)

16.3.3 *Cogeneration Efficiency Perfection*

Generally low-efficiency cogeneration systems like Rankine steam cycles and old back pressure steam turbines (BPST) have been used for cogeneration, but recently superior cogeneration systems are being focused (Dias et al. 2013; Macedo et al. 2001; Pellegrini et al. 2013), which upshot more surplus electrical energy. As suggested by Banco Nacional de Desenvolvimento Econômico e Social (BNDES) and Centro de Gestão e Estudos Estratégicos (CGEE), surplus energy per ton of sugarcane processing is practicable with higher-pressure condensation-extraction steam turbines (CEST) than with BPST as shown in Table 16.5 (BNDES and CGEE 2008; Khatiwada et al. 2012; Purohit and Michaelowa 2007). Hence, conventional sugar mills are able to generate only 10–20 kW of electrical energy by spending about 500 kg steam and process 1 ton of cane (Deshmukh et al. 2013). Advanced sugar mills having dexterous cogeneration systems, on the other hand, can yield electrical energy of about 120 kW with 1 ton of cane processing (Kamate and Gangavati 2009). A further enhancement in power generation is also attainable by following process steam saving techniques with modifications in sugar mills. Such technology lowers down the steam usage of about 280–300 kg ton^{-1} of sugarcane processing including ethanol distillation, the surplus of which can be used to enhance the electricity generation. Fractional use of sugarcane trash further promotes surplus power generation (ISO 2009).

16.3.4 *Efficiency of Cogeneration Systems*

Ensinas et al. (2006) studied four configurations of cogeneration systems that could be applied in sugarcane factories. Configuration system-I comprised steam cycle with back pressure steam turbine. In this case the sugar process governs the steam

Table 16.6 Benefits of configurations

Live steam system	Live steam parameter		Configuration-I				Configuration-II	
	Pressure (bar)	Temperature (°C)	Surplus bagasse (%)		Surplus electricity (kW ton^{-1} cane)		Surplus electricity (kW ton^{-1} cane)	
			Case 1[a]	Case 2[b]	Case 1	Case 2	Case 1	Case 2
LS-1	60	480	9.3	35.4	46.0	24.2	58.1	70.0
LS-2	80	510	7.5	34.1	53.2	29.3	63.3	75.2
LS-3	100	540	5.9	32.9	59.2	33.6	67.4	79.4
Live steam system	**Live steam parameter**		**Configuration-IV**				**Configuration-III[c]**	
	Pressure (bar)	Temperature (°C)	Complementary fuel energy input (MW)		Surplus electricity (kW ton^{-1} cane)		Bagasse deficit for process steam (%)	
			Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
LS-1	60	480	406.7	151.0	180.7	120.2	50	7
LS-2	80	510	415.6	157.3	185.5	123.6	–	–
LS-3	100	540	421.5	161.5	188.7	125.9	–	–

[a] Case 1 (470 kg steam ton^{-1} of cane bagasse)
[b] Case 2 (335 kg steam ton^{-1} of cane bagasse)
[c] Only 314 kg steam ton^{-1} of cane bagasse (Ensinas et al. 2006)

formation by the boilers without condensation system. It is the most common cogeneration system in sugar factories operative during the crushing seasons only (Table 16.6). About 470 kg saturated process steam at 2.1 bar pressure per ton of cane is used leaving 9.3% surplus bagasse and producing electricity of 46 kW ton^{-1} cane for mill processing (LS-1, Case 1). The increase in pressure and temperature of live steam drops the bagasse saving with higher electricity production. Case 2 appeared non-feasible to generate electricity although it saves more bagasse. Configuration-II comprised Rankine cycle with extraction condensation turbine system where condenser has more operation options and flexibility of functioning in crushing and non-crushing times at 0.085 bar condensation pressure. It works best at 2.1 bar process steam using 335 kg steam ton^{-1} cane with some modifications, like vapor bleeding and heating from first to fourth effect of evaporation, repeated usage of process steam, and addition of sixth effect evaporation station in the factory layout. This configuration consumes maximum bagasse in the cogeneration system with surplus electricity of 70–79.4 kW ton^{-1} cane.

Configuration-III relied on a gasifier that converts bagasse into syngas to fuel the gas turbine (Ensinas et al. 2006). In a sugar factory, around 593 Nm^3 syngas ton^{-1} cane could be produced. The exhaust gases from the gas turbine generate 2.1 bar steam in a HRSG for sugar process. Configuration-IV was a BIGCC cycle that also worked with a bagasse gasifier as fuel for gas turbine. The steam generated in a HRSG from thermal energy of exhaust gases is used for sugar process at 2.1 bar, and high-pressure steam operates turbine to generate electricity.

Although Configuration-IV generates high electricity of about 185 kW ton^{-1} cane, configurations III and IV were rated inefficient due to low efficiency of gasification process and requirements of high complementary fuel energy input (150–421 MW) than configurations I and II that operate with steam cycles alone (Ensinas et al. 2006). Hence Configuration-II makes possible the use of all the bagasse for electricity production and offers the possibility of operation of the system during the whole year using a complementary fuel like cane trash (Leal et al. 2013).

In some conformations of biomass gasification, bagasse dryer, gasifier, and gas cleaning system are involved to work for heat recovery steam generator (HRSG) or biomass integrated gasification combined cycle (BIGCC) with exhaust gases to produce steam for the process. With these conformations the HRSG can yield about 140 kW electricity per ton of sugarcane, while a BIGCC-operated plant may provide 200–250 kW surplus energy per ton of sugarcane (Khatiwada et al. 2012; Pellegrini et al. 2013).

Colombo et al. (2014) evolved a special mathematical model to elaborate the energy and material process balances for estimating the effect of different working environments on cogeneration systems for idealizing the process competence. They introduced the term “renewable efficiency” to elucidate the extent of green power that a process plant generates. The new designs may include up to 33 MW of extra bioelectricity to the grids. Hence, sugar plants are being made efficient either by augmenting pressure and temperature of boilers or switching to BIGCC systems (BNDES and CGEE 2008; Khatiwada et al. 2012; Pellegrini et al. 2013). Both plans involve exchange of steam-driven machines with electrical ones. The electrical energy generation with superior turbines let better and easy energy conversion that results in more surplus of electrical energy.

Colombo et al. (2014) proposed two repowering layouts: In the first option superheated Rankine cycle was placed in conjunction with the boiler C scheme that works at 2.7 bar of regeneration and condensing pressure. The scheme involves turbine inlet, regeneration bleeding, process bleeding, turbine outlet, condenser outlet, process condensed water, addition of regeneration vapor, and pump and boiler’s inlet. The second scheme was analogous to first option with medium pressure reheating system. This scheme worked for similar time in a year with immediate access of 295 MW of fuel energy. In Option II, the expansion was divided into two blocks of turbines (VHP inlet and VHP outlet) because of the reheating at first place. These schemes verified 11.0 and 12.7% internal rate of return for Options I and II, respectively.

16.3.5 Use of Cane Trash as Cogeneration Fuel

Cane trash is the dried leaves in the form of field residue left after harvesting and cleaning of the cane stalk. It could be one of the most interesting complementary fuels for the sugarcane factories. It can be recovered from the cane fields to the quantity of about 125 kg ton^{-1} sugarcane (Leal et al. 2013; Macedo et al. 2001) and can be used as fuel in addition to natural gas during off-seasons (Khatiwada et al. 2016; Rodrigues et al. 2003). Its LHV is 12.6 MJ kg^{-1} for which cogeneration plants have been partially shifted on this fuel in some countries.

16.3.6 Advantages of Cogeneration

Cogeneration's role is utmost in current climate change scenario where thwart in global warming by mitigating CO_2 emissions is a priority in international agenda. It could also be a fascinating source of income for sugarcane factories in future benefitting from the mechanisms represented in Kyoto protocol, like Clean Development Mechanisms. The following are the other benefits of cogeneration system (Table 16.7).

Moreover, cogeneration systems have remarkably superior efficiency as against conventional thermoelectric electricity generation as presented in Table 16.8.

However, apart from benefits of cogeneration, there are also some challenges which need to be tackled:

- High internal implementation and equipment costs
- Additional maintenance, repair, and operation (MRO) expenses
- Unpleasant price for sales of excess power
- More price of bagasse (Mauritius US\$3.70 ton^{-1}, Pakistan US\$2.50 ton^{-1}) compared to the price of other electricity fuels

Table 16.7 Benefits of cogeneration systems

Financial	Operational	Environmental
Reduce primary energy cost up to 30%	Improve the security of electrical supply	Lessen the fossil fuel usage
Reduce energy expenses by up to 20%	Remove the utility power purchase	Augment energy efficiency
Stabilize the risks linked with fast rising energy prices	Develop the safety of heat provision	Decrease the greenhouse gas emissions
Provide extra revenue by selling surplus power	Eliminate the need for valued electrical connection upgrades	–
–	Offer electricity, heat, and cooling concurrently	–

Source: De Rosa and Salvadori (2007)

Table 16.8 System efficiency of thermoelectric and cogeneration systems

System efficiency (%)				
Cycle	Otto/diesel	Rankine	Brayton	Combined cycle
Thermoelectric	40–50	30–45	34–45	~55
Cogeneration	~60	50	70–75	70–75

Source: De Rosa and Salvadori (2007)

For bagasse energy development, it is essential to have sugarcane processing modernization for efficient bagasse usage, national grid's transmission lines' connection with the bagasse/mill power plants, and use of coal, gas, sugarcane trash, or other renewable sources as off-season fuel to ensure regular power export.

16.4 Biogas from Sugarcane Pressmud, Bagasse, and Vinasse

Domestic and industrial fuel demands are mainly met with oil, coal, natural gas, forest wood, and woody material which are limited and being exploited constantly, whereas a lot of industrial, agricultural, and domestic wastes are thrown as such causing environmental pollution. Biogas generation from the anaerobic digestion has been revealed to be one of the viable technologies to find an appropriate application of these wastes.

Sundaranayagi et al. (2017) described that anaerobic digestion process of solid wastes convolutedly involves several groups of anaerobes. Methane is a major component of biogas (60–65%) followed by carbon dioxide (30–40%) and hydrogen (0–1%). Anaerobic digestion comprises four biochemical mechanisms called hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The anaerobic digestion results in biopolymers' conversion to monomers, followed by the conversion of soluble monomers into short- and long-chain fatty acids by acidogens. Subsequently, acetic acid production takes place along with small quantities of hydrogen and carbon dioxide (by acetogens), and finally, methane and carbon dioxide are generated through methanogenesis.

Production of biogas from waste and organic residues has been investigated for decades (Marek et al. 2014). General materials for biogas production are lignocellulosic biomasses, organic compounds, animal wastes, industrial water, and municipal solid wastes (Hadiyarto et al. 2017; Brown et al. 2012; Wilawan et al. 2014). A combination of water, sheep dung, and hyacinth in a ratio of 84:12:4 can produce 360 L biogas per kg of substrate (Patil et al. 2014). Oleszek et al. (2014) produced biogas from weeds and grass varieties of walnuts. Similarly, sugarcane residues and sugar industry's wastes like bagasse, pressmud, trash, and vinasse have been effectively employed for biogas production alone or in combination with other organic materials (Rouf et al. 2010; Sathish and Vivekanandan 2015; Talha et al. 2016).

Bagasse, as discussed earlier, is a lignocellulosic residue of sugar mills comprising mainly cellulose, hemicellulose, and lignin (Maryana et al. 2014; Talha et al. 2016). Cellulose and hemicelluloses are long-chain sugar monomers that can be converted into biogas through pretreatment and hydrolysis (Eshore et al. 2017; Hendriks and Zeeman 2009). Mechanical, thermochemical, alkali, or acid pretreatments convert complex organic molecules of bagasse and other compounds into simple sugars, amino acids, and fatty acids (López González et al. 2013, 2014; Modenbach and Nokes 2014).

Sumardiono et al. (2017) obtained biogas yield of 51.04 L kg^{-1} with substrate combination of bagasse treated with 2% NaOH for 24 hours and 20% cow's rumen. Anaerobic codigestion of pressmud and 1 N NaOH treated bagasse resulted in higher cumulative biomethane yield than untreated substrates or the substrates alone (Talha et al. 2016). Further, mixing of pressmud with bagasse at 25:75 ratio (C/N ratio 24.70) yielded the best cumulative biomethane and was considered the efficient method of biogas production. Less C/N ratio (9.86) of pressmud lowers the biomethanation, whereas mixing it with a higher C/N ratio (~27) bagasse-like substrates (for optimum C/N ratio of ~25) elevates biomethanation. Anaerobic digestion of pressmud starts in a short time of 4–5 hours to produce biogas and pressmud with bagasse yields biogas containing 52% methane (Sundaranayagi et al. 2017). In another biomethanation study, maximum biogas yield was obtained as 0.68 m^3 m^{-3} of 1:1 pressmud to water ratio resulting in methane concentration of 67% at 30–35 °C mesophilic conditions (Sathish and Vivekanandan 2015).

Literature reveals that nickel, cobalt, and iron are desired elements for microbial activity, which can further be compensated through addition of deficient nutrients in the substrate for improved biogas yields (Sundaranayagi et al. 2017). Methanation of pressmud along with cow dung inoculum and trace elements (Ni, Co, and Fe) for 30 days revealed that addition of Fe yielded the maximum biogas (520 mL day^{-1}) in the anaerobic digestion process. Sundaranayagi et al. (2017) also suggested that a proper anaerobic digestion needs a balance in nutrition especially carbon, nitrogen, phosphorous, and sulfur. Moreover, too high C:N ratio may also have depressing effect on microbial functioning.

Vinasse is a sugar distillery's waste that is environmentally unhealthy if disposed of or used untreated in agriculture, due to biological oxygen demand (BOD) of about 25,000 mg L^{-1} and chemical oxygen demand (COD) of ~48,000 mg L^{-1} (Baez-Smith 2006). However, it has high potential for biomethanation with a possibility of more than 70% conversion of its COD to methane during anaerobic biodigestion (Rao 1999). An alcohol distillery producing 500 L ethanol day^{-1} has the ability to produce 73,000 m^3 biogas day^{-1} from vinasse in its allied biodigestion plants that corresponds to about 14.6 L m^{-3} of vinasse (de Souza et al. 2011; Salomon et al. 2011). The anaerobic biodigestion treatment of vinasse preserves its fertilization potential (phosphorus, potassium, and nitrogen) and decreases its BOD and COD up to 90% and 70%, respectively, to make it safer for agricultural use (Baez-Smith 2006; Salomon et al. 2011).

A biochemical methane potential assay for the energy potential of sugar industry wastes was performed by Janke et al. (2015). It revealed that methane yield varied considerably with the nature of substrate, whereas maximum methane yield was obtained from bagasse and minimum from vinasse on fresh mass basis (Table 16.9). Such results were mainly attributed to the variation in substrate properties and water contents. Hence, the energy-related applications of sugarcane industry not only limit to ethanol and bioelectricity production, but the same industry has great potential to serve for biogas supplies as well.

Table 16.9 Biochemical methane potential of the sugarcane waste after 35 days of assay

Substrates	Methane yield[a] (NmL g_{VS}^{-1} or NmL g_{COD}^{-1})	Methane yield (Nm^3 ton_{FM}^{-1})	K (day^{-1})
Straw	228 ± 9.3	129 ± 5.7	0.089
Bagasse	281 ± 4.5	150 ± 2.0	0.111
Pressmud/filtercake	260 ± 4.3	54 ± 1.3	0.143
Vinasse	274 ± 7.6	8 ± 1.0	0.243

VS volatile solids, *COD* chemical oxygen demand, *FM* fresh biomass (Janke et al. 2015)
[a] Methane yield of vinasse is given in NmL g_{COD}^{-1}

16.5 Bioproduct Production at the Sugar Industry

In addition to first- and second-generation ethanol, bioelectricity, and biogas, the generation of value-added products and utilization of processed by-products can help offset the cost associated with sugar and ethanol production. Such is the case with companies like BlueFire Renewables, Virdia (acquired by Stora Enso), Gevo, Amyris, Codexis, LS-9 (acquired by REG Life Sciences, LLC), and Virent who have shifted their research interest from second-generation ethanol to specialty products.

Inhibitory by-products generated during the processing of ethanol from lignocellulosic biomass can be recovered and used as potential platform chemicals to many bio-based products including silage and animal feed preservation, food preservatives, catalysts, and plasticizers from formic acid and levulinic acid and in the production of biodegradable polymers as in the case of acetic acid (Choi et al. 2015; Hietala et al. 2016; Le Berre et al. 2014; Ranjan et al. 2009). HMF can be converted to levulinic acid, dimethylfuran, 2,5-furandicarboxylic acid, and dihydroxymethylfuran, which are building blocks in the manufacture of alternative fuels, polymers, foams, and polyesters (Rosatella et al. 2011). Furfural has several applications as an additive in anti-acids, inks, fungicides, adhesives, and flavoring agents (Bozzell and Petersen 2010: Cai et al. 2014).

Furthermore, the effective extraction and recovery of lignin-derived phenolic compounds (vanillin, phenol, coumaric acid) and lignin by-products (technical lignins) can generate additional revenues, while the remaining lignin is burned for energy. Lignin-derived phenolic compounds have applications in the food, pharmaceutical, and cosmetic industries (Tejado et al. 2007; Zhang et al. 2013). Technical lignins (complex phenolic polymers) possess antimicrobial, anticarcinogenic, and antioxidant properties with potential applications in food, medicine, polymers, and cosmetics (Espinoza-Acosta et al. 2016). Alternative means of utilizing the hemicellulose sugars could be also explored to produce alternative chemicals such as lactic acid (for use in packaging, prosthetics, and drugs), furfural, and xylitol (for use as a sweetener and preservative and in tooth remineralization) (Machado et al. 2016; Martinez et al. 2013; Naidua et al. 2018).

16.6 Conclusion

Sugarcane is an important source of food and fuel energy. Its molasses and bagasse have tremendous potential to produce ethanol (through fermentation) and bioelectricity (through cogeneration), respectively. Furthermore, sugar industry can also serve the provision of biogas utilizing surplus of its wastes, pressmud, and bagasse. Hence, recycling and renewability of resources of sugar industry can play an utmost important role in generating various forms of renewable bioenergy, to mitigate the CO_2 emissions and contribute toward tackling climate change. Moreover, such applications are also fascinating for sugarcane factories keeping in view the economic benefits. Only a few countries like Brazil are exploiting these resources while others need to adopt similar models to lessen the reliance on fossil fuels and energy.

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Chapter 17
Challenges, Constraints, and Limitations of Cane Biofuels

Fabio R. Marin, Murilo S. Vianna, and Daniel S. P. Nassif

17.1 A Brief Historical Perspective

Sugarcane (*Saccharum officinarum L.*) is one of the world's most productive crops, with biomass accumulation rates as high as 550 kg ha^{-1} day^{-1}. Apart from being the main source of sugar in the world, the ability to produce large amounts of biomass over a relatively short time makes this species extremely attractive in a biomass-dependent economy (Moore and Botha 2013). Although there are various ways ethanol fuel can be produced, the most common way for large-scale production is via sugar fermentation. Over the last three decades, sugarcane has emerged as the second largest source of biofuel, with major social, economic, and environmental importance in many tropical and subtropical countries (Carpio and Simone de Souza 2017; Scheiterle et al. 2018). Currently, it is the sixth most economically significant crop and the second most important C4 species, after maize (Sage et al. 2014).

In 2016, approximately 27 million hectares of sugarcane were cropped around the world (Fig. 17.1), producing nearly 1.9 billion tons of harvested cane, which gave an average yield of 70 tons ha^{-1} as per Food and Agriculture Organization Statistics (FAOSTAT 2018). More than 70% of the global sugarcane crop are produced in Brazil, India, China, Thailand, and Pakistan (FAOSTAT 2018). Brazil has become the largest sugarcane producer in the world being responsible for nearly a half (46%) of the global production.

In terms of ethanol production, the United States is the world's largest producer of bioethanol (BE), having produced nearly 16 billion gallons in 2017 alone,

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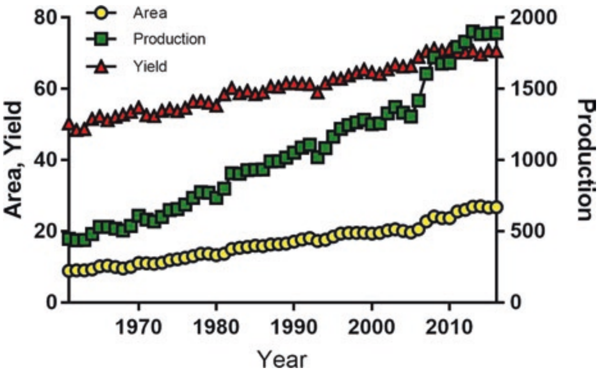

Fig. 17.1 Trends in sugarcane harvested area (10^6 ha), production (10^6 ton), and fresh stalk yield (ton ha^{-1}) in the world between 1961 and 2016. (Source: FAOSTAT 2018)

representing nearly 60% of global production. Renewable Fuels Association (RFA 2017) mentions that together, the United States and Brazil produce 85% of the world's ethanol. Nevertheless, the vast majority of US ethanol is produced from corn starch, while Brazil primarily uses sucrose from sugarcane. Sugarcane ethanol is produced from the fermentation of sugarcane juice, molasses, and more recently, cellulose through so-called "second-generation" approaches (Goldemberg et al. 2014).

Brazil is the major cane ethanol producer, where the sugarcane ethanol industry has been under development since the early twentieth century, and it was firmly established in the late 1970s by the National Bioethanol Program called *ProAlcool*. At that time, Brazilian adoption of mandatory regulations to blend 25% BE with gasoline played a decisive role in the success of the program, which also encouraged the car manufacturers to produce engines running on pure hydrated ethanol (100%) (Walter et al. 2014).

As reported by the International Energy Agency (IEA), the European Union (EU) stands as the third major ethanol producer (5%) in the globe with considerable heterogeneous feedstock supplies including 39% from maize, 30% from wheat, 20% from sugar beet, 7% from other starch-rich cereals, and 3% from lignocellulosic and other new materials (IEA 2016). China as an emergent economy began to use corn-based ethanol in 2002 and reached 1.92 million tons in 2012, making it the third largest fuel ethanol-producing and ethanol-consuming country in the world. Nowadays, China produces ethanol from sweet sorghum and cassava, in Northeast, North, and Northwest China and some areas of the Huanghuai River Delta, mainly in saline-alkaline lands (Ge et al. 2014). Although ethanol yield from sugarcane is almost twofold higher than corn and other energy crops (Goettemoeller and Goettemoeller 2007), the cost of deployment of the whole sugarcane-based ethanol production system is one of the major barriers for developing countries (Crago et al. 2010). In addition, the development of other energy sources for ordinary transportation vehicle, such as electric vehicles, might reduce the ethanol demand in the coming decade.

17.2 New Clean Fuel Technologies (Electric Cars) Versus Ethanol

Transportation sector accounts for approximately 20% of global primary energy use with nearly half of this use originating from passenger vehicles (Nanaki et al. 2016). In the dawn of the automotive industry (mid-nineteenth century), there were basically three technologies competing for market domination: internal combustion engine (ICE), steam cars (SC), and electric vehicles (EVs). In spite of its low energy efficiency (<20%), ICE technology prevailed, among others, due to its faster advances and new technologies to solve the engine start-up and water leakage problems (Garcia-Valle and Peças Lopes 2012). With seemingly unlimited supplies of low-cost petroleum in the last century, the poor efficiency of the ICEs was initially less important than the power, convenience, and reliability they provided (Ohlrogge et al. 2009).

Nowadays most vehicles and equipment across all transport modes are still powered by ICEs worldwide, with gasoline and diesel as the main fuels for light-duty vehicle (LDV), gasoline for two- and three-wheelers and small watercrafts, diesel for heavy-duty vehicles (HDV), diesel or heavy fuel oil for ships and trains (other than those using grid electricity), and kerosene for aircraft turbine engines (Intergovernmental Panel on Climate Change [IPCC] 2014). Alternative source of fuels for ICEs had been tested since the beginning of the automotive industry (Bae and Kim 2017; Srivastava and Hancsók 2014); however, the global deployment of any alternative fuel was mainly limited due to the competitive price of petroleum and lack of technology to produce alternative fuels in large scale. Nevertheless, BE and biodiesel have emerged as the main alternative sources for powering the ICE-based LDV and some HDV leveraged by the petroleum crisis in the 1970s, oil price shock in 1990, and energy crisis in 2000 (Hamilton 2008).

With the rise of oil prices and the increasing awareness on climate change impacts, renewable liquid biofuels (and other renewable energy sources) gained global attention during the last decade (Goldemberg 2007; Ohlrogge et al. 2009). Advances on BE, biodiesel, pyrolysis bio-oil, drop-in transportation fuels (biomass-derived liquid hydrocarbons that meet the existing petrol distillate fuel specifications being ready-to-use in gasoline-based engines), and production processes were then achieved to supply the increasing demand for renewable fuels and offset climate change (Guo et al. 2015). Although the energy equivalent of ethanol is around 70% lower than that of crude oil-based fuels, the combustion of ethanol is considered cleaner because it contains oxygen (Vohra et al. 2014).

In the short term, Brazilian sugarcane BE could provide the equivalent of 3.8–13.7% of global crude oil consumption by 2045 under projected climate change while protecting forests under conservation and accounting for future land demand for food and animal feed production (Jaiswal et al. 2017). In addition, large commercial BE is currently produced from starch/sugar-based crops including sugar beet, corn, wheat, barley, and potato been not restricted only to the tropical lands (Guo et al. 2015), and indicating the BE could be widely produced around the world.

Coupled with biofuel production, new ICEs need to be modified during manufacturing, to accommodate higher blends as exemplified by "flex-fuel" gasoline engines in which ethanol can be used as the main fuel. Only drop-in fuels could be deployed without further modification on ICEs, but its large-scale production may only be achieved in the long term (IPCC 2014).

In contrast to biofuels, new propulsion systems, including electric motors powered by batteries or fuel cells, turbines (particularly for rail), and various hybridized concepts, have been developed in the last decade. Battery electric vehicles (BEVs) have no tailpipe emissions and potentially very low fuel production emissions (when using low-carbon electricity generation) (Kromer and Heywood 2009). BEVs operate at a considerably higher efficiency of around 80% compared with about 20–35% for conventional ICE LDVs. Despite this increased energy efficiency, electric vehicles were always an alternative technology for transportation sector, but the high battery cost, lack of a standardized recharging infrastructure, and reduced driving range were barriers for competitive price and deployment (Nanaki et al. 2016). In the last years, nevertheless, BEVs gained attention mainly in Europe and Asia due to technological developments and increased focus on renewable energy (Stocker 2014). From then on, two main categories of electric vehicles emerged: the all-electric propulsion vehicles named plug-in electric vehicles (PEVs) and the plug-in hybrid electric vehicles (PHEVs).

The mass production of PEVs was initiated by Tesla Motors in 2008 with lithium-ion (Li-ion) battery technology, while major vehicle manufacturers developed PHEV models that could self-recharge by its onboard engine and generator. In addition, the PHEVs typically can operate on battery's electricity for 20–50 km but emit CO2 only when their ICE is operating (Hannan et al. 2014). Besides, the rapidly decreasing scenario of Li-ion battery's costs also favored the PEV market, which became dominant in major developed countries (Fig. 17.2). Although only 0.2% of all passenger vehicles, approximately two million electric vehicles, are currently on the road worldwide (Fig. 17.3), the increasing market penetration and government incentives in many developed countries project that PEV + PHEVs will represent more than 10% of global vehicle fleet by 2030 (IEA 2017). In some European countries, such as the Netherlands and Spain, the phaseout plan for ICE vehicles will take place in the next decade, with exclusive sales of EVs by 2030.

As the number of electric cars in developed countries continue to increase, this technology still has a long way to go before reaching deployment scales capable of making a significant dent in global oil demand and greenhouse gas emissions (GHG). In 2012, the global biofuel utilization reached 10% of the world's total energy consumption and 80% of the total renewable energy production (Chum et al. 2014; Haberl et al. 2013). Bioethanol and biodiesel are being widely produced to complement the rapidly depleting petroleum reserves and by 2050 are projected to be the dominant fuels to power passenger cars and heavy vehicles (Guo et al. 2015). Automobiles powered by electricity, natural gas, and hydrogen are emerging, but currently existing liquid fuel supply systems might restrict them from becoming the mainstream technologies within developing countries in the next decade. Even in developed countries, the energy grid infrastructure to fully supply electrical energy

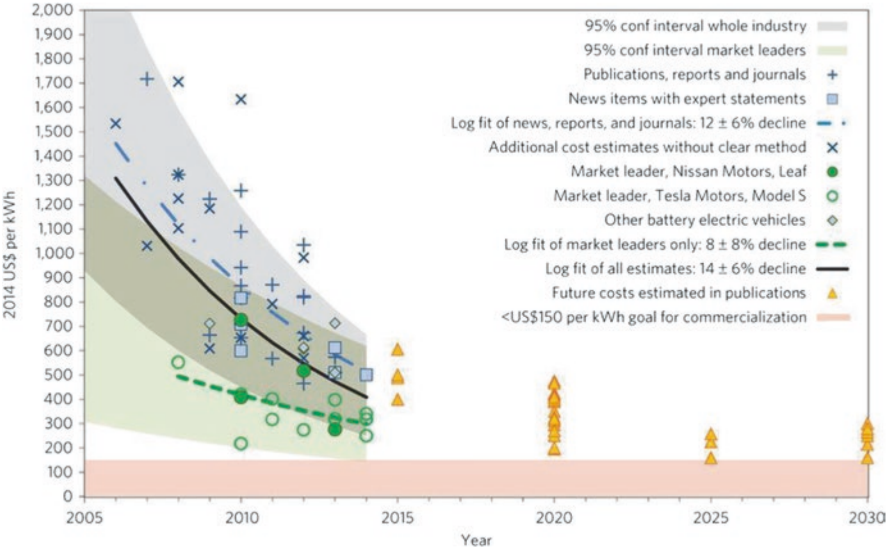

Fig. 17.2 Cost of Li-ion battery packs in BEV. Data trace both the reported cost for industry and the costs for market-leading manufactures. Reaching the costs of US$150 per kWh is considered as the point of commercialization of BEV (Nykvist and Nilsson 2015)

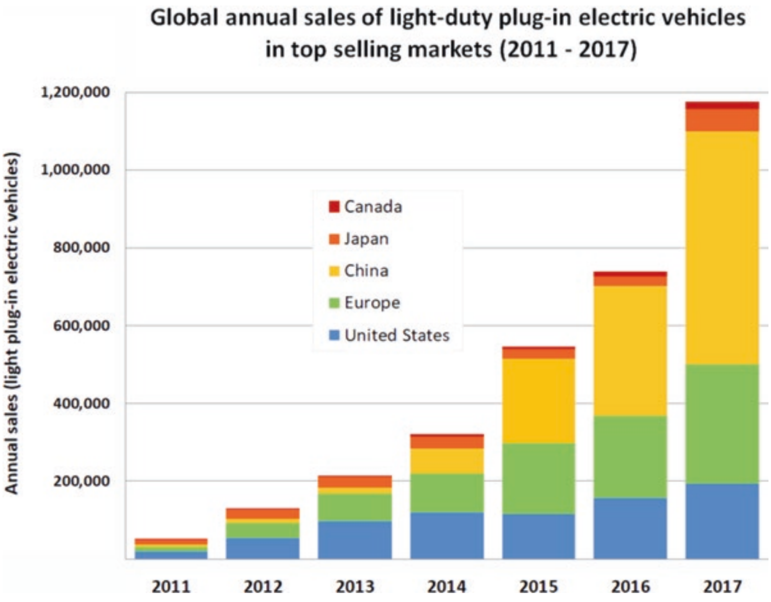

Fig. 17.3 Annual sales of light-duty plug-in electric vehicles in the world's top markets between 2011 and 2017 (IEA 2017)

for recharging EVs is challenging (IEA 2016). Although ethanol remains a compelling option for many developed and developing nations in the coming decade (Hess et al. 2016; Jaiswal et al. 2017; Marin et al. 2016), sugarcane-based ethanol yet suffers from cost competitiveness with other agricultural feedstocks. Moreover, the increasing trend of phaseout of ICEs seems inevitable and might drastically constrain not only sugarcane ethanol production but the majority of ethanol demand.

17.3 Socioeconomic Challenges in Developing Countries

During the last decade, biofuels have gained importance due to economic, social, and environmental factors (Goldemberg 2007). At the initial phases of production as an energy source, ethanol faced the barriers of adaptation and acceptance of every new technology. Ethanol production as biofuel gained attention after the oil crisis and was considered as an alternative liquid fuel to buffer the fossil fuel dependency (Hira and de Oliveira 2009). Therefore, in contrast to other new technologies, ethanol was not a revolutionary invention, and the acceptance by final consumers was arduous. In comparison to gasoline, ethanol is around 30% less efficient, reducing cars' autonomy; moreover, the issues with start ignition on cold regions were a barrier for ethanol usage in temperate climates (Nakata et al. 2006). These problems were overcome by the regulation of ethanol prices in terms of gasoline efficiency, adaptation of starting ignition for colder temperatures, and mandatory (5–27%) or optional ethanol blends (10–90%) to gasoline, adopted in many countries, including the United States, European Union, China, and Latin America (Goldemberg 2007).

Sugarcane-based ethanol also had the additional challenge of having a bad reputation of precarious labor conditions continuously associated to the slavery on sugarcane plantations (Rocha et al. 2010). Further, the sugarcane burnt for harvesting on large plantations increased respiratory illness and air pollution in nearly located urban areas (Barbosa et al. 2012; Paraiso and Gouveia 2015). To overcome these social barriers, the mechanization of harvesting and prohibition of burnt sugarcane took place in many producing regions. However, the mechanization was limited to large and/or technified producers; thus it was mostly adopted in Australia, the United States, South Africa, China, and Brazil. Regarding India, the second major sugarcane producer in the world, harvest mechanization is not well established as the Indian agriculture is characterized by small and scattered holdings, and sugarcane cultivation is no exception (Singh et al. 2011).

Despite the great advances in terms of labor saving, the harvester technology remains almost unaltered since its conception in the early 1950s, featuring low efficiency as well as capacity which in turn yields higher soil compaction, structural damage to ratooned plants, and reduced sugarcane plantation life-span (Ma et al. 2014; Rodríguez et al. 2012). In addition, many agricultural practices are stagnated due to machinery requirements. In this reference, the row spacing of sugarcane plants, an important feature for agricultural practice dimensioning, is generally dictated by the harvester design and capacity, which does not seems the best for assuring higher sugarcane yields.

Yet, in Brazil, the establishment of BE as a broad commercial fuel was achieved after the civil society, agricultural sector, and car manufacturers well accepted the federal intervention on ethanol market during a military regime, with a focus on reducing oil imports which consumed one-half of the total currency from exports (Goldemberg 2007). After a period of strong growth during the 1980s, a huge sector depression was then witnessed during the 1990s with the end of government subsidies and low oil prices (de Moraes and Zilberman 2014). In the 2000s, a new cycle of high oil prices and lowland prices and a general mood of optimism around the country resulted in building a large number of new mills (green-field projects) (Marin et al. 2016; Scarpare et al. 2016).

After the 2007–2008 global financial crisis, the sector fell deeply into debt and was unable to raise finance from the banks, forcing several mills to reduce crop inputs (fertilizers, herbicides, and diesel), cut its workforce, and change important agricultural management practices (e.g., seed production, cane field renewal, and mechanization) (Scarpare et al. 2015), resulting in a decrease in number of operating mills, from more than 430 to currently 371 across Brazil. However, most of those that survived the economic difficulties were reengineered to improve their operating processes and to reduce running costs; despite the high financial costs which still threaten some of them, most are showing signs of growth since early 2015 (Marin et al. 2016).

For instance, sugarcane crop production increased between 2002 and 2013 in Brazil, with an average rate by +10% per year, whereas ethanol production augmented by 40% (de Moraes and Zilberman 2014). This higher ethanol production was achieved mainly due to increased ethanol demand boosted by the *flex-fuel* technology, introduced in Brazil by 2003. The flex-fuel vehicles are capable of running with all combination of gasoline and hydrous ethanol blends (Gilio and de Moraes 2016). In 2013, more than 2.7 million vehicles were marketed in Brazil, and close to 90% of them had flex-fuel technology (Associação Nacional dos Fabricantes de Veículos Automotores [ANFAVEA] 2018), demonstrating the importance of the sugarcane crop and ethanol in Brazil. Despite the remarkable production increase in the 2000s, more than 80% of the sugarcane production gain in this period was accounted by expanding the crop to new marginal areas rather than agricultural intensification (Scarpare et al. 2016). Many of these new sugarcane crop fields were faced with new challenges when expanding into nontraditional regions mainly related to (i) climate, where intense water shortages throughout the year substantially reduced yields and increased the risk of death to plants; (ii) infrastructure, where logistics and operation of large areas become impractical without proper roads and machinery; and (iii) distance from distribution centers and exportation that increases ethanol prices. Because final consumer can choose between gasoline and ethanol, gasoline becomes more economically attractive to final consumers.

The benefits from expansion of the sugarcane industry were, for the most part, derived from the sector's downstream segment, and the socioeconomic impacts of a sugarcane processing plant are likely to extend beyond borders of the municipality where the plant is located (Gilio and de Moraes 2016). According to Da Costa et al. (2013), an increase of 5%, 10%, and 15% in ethanol consumption to the detriment of gasoline had a potential job creation of 40,000, 79,000, and 118,000, respectively, resulting in a great socioeconomic impact in the country. In 2010, according to the same authors, the sugar-energy sector employed almost 1.2 million workers, about 20% of all formal agricultural jobs in that year. Ethanol is recognized as a renewable fuel, with great potential for the developing countries, like Brazil whose renewable energy program based on sugarcane has attracted investments worldwide (Goldemberg 2007). Therefore, in developing countries, ethanol has great importance because, apart from being a clean fuel, it has a high impact on the economy.

After 2010, following advances in second-generation ethanol production from lignocellulosic wastes, cane ethanol again gained attention because of its high potential for both first- and second-generation routes. Second-generation BE production fulfills the impractical gap of the first generation since it employs nonedible feedstock sourced from agriculture and forestry wastes (Aditiya et al. 2016). Nevertheless, this technology is still under testing for large-scale and efficient production. The cost of production for 1 L of second-generation ethanol is around 30% higher than the first generation; however it is expected that the prices of second-generation ethanol will become competitive by 2025 (Milanez et al. 2015).

In practical terms, sugarcane mills can produce sugar, ethanol, electricity, and feedstock for paper and plastic industries from the harvested biomass. The quality of agronomical practices and transportation are considerable factors on ethanol production and prices. In contrast to other crops, sugarcane yield ranges from 60 to 100 ton ha^{-1} year^{-1} imposing a relatively complicated challenge to logistic operations because of post-harvest losses, as sugars within stalks degrade rapidly after harvest and the crop cannot be stocked like cereal crops. Considering the example of Brazil, harvesting period usually lasts from March to November, and because most of the mills operate continuously, the field harvesting operation shifts are 24/7 in many Brazilian regions. Real-time logistic operations are one of the major demands of the sector due to continuous crushing and harvesting and also because the biomass is transported by trucks (*treminhões*) having load capacity of around 60 tons. If the Brazilian average sugarcane yield is 75 t ha^{-1}, for the Raízen group (~950,000 ha), more than 1,100,000 payloads would be needed to transport all their sugarcane biomass to mills in a single season. For a crushing season of 8 months (~240 days from March to October), Raízen's logistic department should manage the incredibly high average number of 4583 sugarcane payloads per day across their plants, without any unexpected issues.

In practice, the sugarcane harvest and transport are not deterministic (Lamsal et al. 2017). There are uncertainties in both operations: (i) harvesters may break down at the fronts; (ii) the weather may cease harvesting; (iii) the vehicles may become inoperative en route to the mill or to the fronts. Other modes of transportation seem more operationally attractive, exemplified by the railroads used for sugarcane biomass transfer by the Australian Industry. However, such infrastructure requires higher cost of deployment and government incentives. Many of the mentioned challenges are opportunities for real-time logistic platform solutions.

17.4 Challenges Related to Sugarcane Production and Expansion

Sugarcane is a perennial grass adapted to tropical and subtropical climates (Moore and Botha 2013). This feature limits its production to a major part of developing countries located at South America, Africa, the south of Asia, and Oceania. Moreover, given that sugarcane plants are considerably sensitive to water shortages, optimum regions for sugarcane expansion should present a consistent amount of rainfall throughout the year (Scarpare et al. 2016). Although irrigation appears as an attractive solution for water depletion, the infrastructure required for a mill establishment and/or biomass transportation is challenging, in remote areas of the developing countries.

During the last decade, concerns about food security, greenhouse gas emissions, and loss of habitat for biodiversity from direct and indirect land-use change are recognized as important issues for evaluating future options to achieve higher crop production (Burney et al. 2010; Dias De Oliveira et al. 2005; Laurance et al. 2014; Lepers et al. 2005; Vermeulen et al. 2012). The challenge is to increase sugarcane yields on existing farmland given concerns about conversion of grassland and rainforest to crop production and rapidly increasing global demand for sugarcane ethanol. A key issue, therefore, is the extent to which the rate of yield gain can be accelerated above the yield trajectory of the past two decades to achieve greater sugarcane production through higher yields without further expansion of sugarcane production area. Considering the Brazilian case, while sugarcane production has more than doubled from 2000 to 2013, 90% of this increase came from the expansion of sugarcane production area and only 10% from yield increases.

Yield gap analysis provides a robust quantitative framework to answer this issue (Lobell et al. 2009; van Ittersum et al. 2013). Simulations made by Marin et al. (2016) showed the upscaled national average attainable yield (Yw) estimated for sugarcane in Brazil was 134 Mg ha^{-1}. Given the current national average actual yield (Ya) of 82 Mg ha^{-1}, the average yield gap in the country (Yg) is 52 Mg ha^{-1}, which represents 38% of Yw. Figure 17.4 shows variation in Yw and Ya (expressed as % of Yw) across the major climate zones in which sugarcane production takes place in Brazil.

The interesting point noticed by the authors was that maintaining the historical rate of yield gain of 0.85 Mg ha^{-1} year^{-1} (S1) will require a respective 5% and 45% expansion in sugarcane production area to meet the low (LP) and high production (HP) projections by 2024, which represents 0.4% year^{-1} and 4% year^{-1} annual increase in production area (Fig. 17.5). The S1 scenario assumes that the expansion in sugarcane area will occur in areas with Yw similar to average Yw of 134 Mg ha^{-1} estimated for Brazil in this study. If sugarcane expansion were to take place in harsher rainfed environments, or on poorer soils, the additional land requirement would be greater. Nevertheless, the estimated land requirement to satisfy sugarcane demand by year 2024 seems modest under the LP scenario, and though much greater under the HP scenario, area expansion is still much smaller than the rate of increase

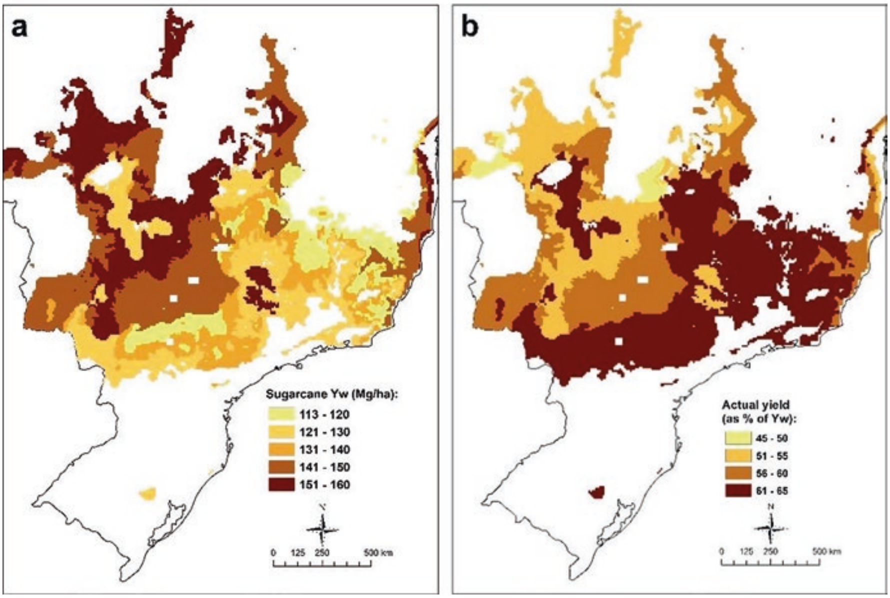

Fig. 17.4 Maps of (**a**) water-limited yield potential (Yw, Mg ha^{-1}) and (**b**) rainfed actual farm yield (expressed as percentage of Yw) for sugarcane across the major climate zones where sugarcane is produced in Brazil. (Reproduced from Marin et al. (2016). Permission – https://drive.google.com/open?id=1vt3TLGEOahhhhUkuyjoy2RD2XS8n65wq)

in sugarcane area that occurred from 2004 to 2013 (7.5% per year). If research and extension focused on closing the current Yg using improved management and best available cultivars to close the exploitable yield gap such that average farm yields reach 80% of Yw by 2024 (S2), equivalent to an average national yield of 107 Mg ha^{-1}, it will be possible to meet the LP sugarcane demand while reducing land requirements by 18% compared to current sugarcane area (Fig. 17.5).

In contrast, closing the exploitable yield gap on existing sugarcane area will not be sufficient to meet the HP demand scenario, and a 13% increase in sugarcane area will be required, which represents a rate of area expansion of ca. 1.2% year^{-1}. However, the area increase under the HP-S2 scenario is 71% less than required by the "business as usual" HP-S1 scenario. However, a yield gain of more than threefold (from 0.85 to 3.2 Mg ha^{-1} year^{-1}) given the technological development trend seems unlikely to happen by 2024, and sustaining such high rates of gain during the next 10 years to get close to the exploitable yield appears to be an arduous task.

Climate change is another issue to be considered when evaluating scenarios for future production of sugarcane. This is because global climate variability and change caused by natural processes and anthropogenic factors may result in major environmental issues that will affect the world during the twenty-first century. Recent estimates of temperature increase from the IPCC in the Fifth Assessment Report (AR5) are in the range of 0.3–0.7 °C in 2016–2035, depending on the green-

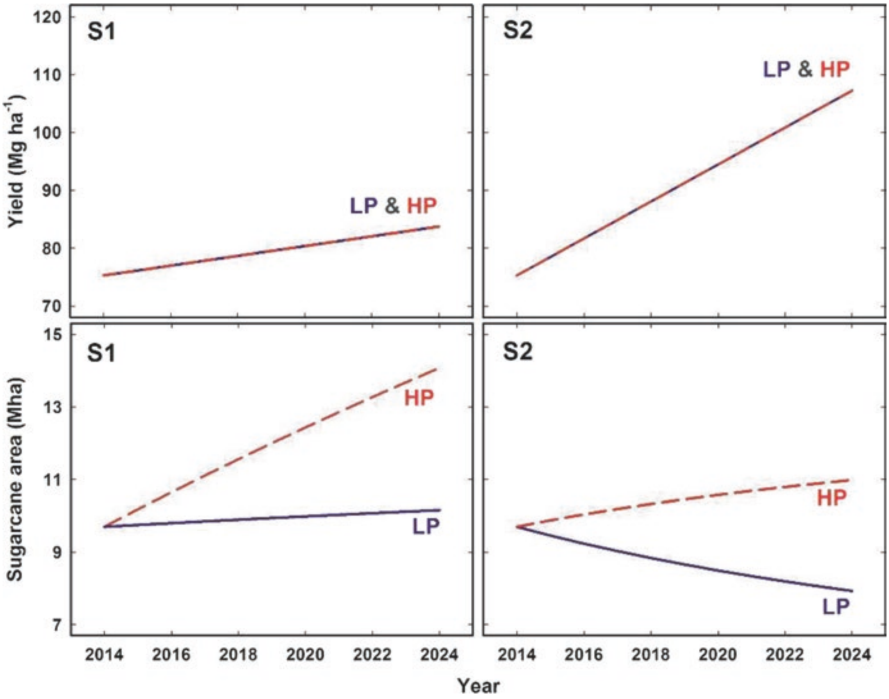

Fig. 17.5 Pathways to meet future sugarcane demand in Brazil under four scenarios showing sugarcane yield (upper panels) and sugarcane area (lower panels) required to meet 2024 "low" (LP, blue solid line) and "high" (HP, red dashed line) production projections for two scenarios: demand met with historical rate of yield gain (S1, left panels) and demand met by closing the exploitable yield gap to 80% of water-limited yield potential (S2, right panels). (Source: Marin et al. (2016). Permission – https://drive.google.com/open?id=1XrEkY4vs8UTtmmVVRVL1TTdV7aYFNxmG)

house gas emission scenario (Stocker 2014). Climate variability and climate change are projected to result in changes in soil moisture and the frequency of extreme high-temperature events, floods, and droughts in many locations (Alexandrov and Hoogenboom 2000).

Crop simulation models have been used to assess the yield responses of various crops to anticipate the future climate changes at large spatial scales. For sugarcane, however, few studies have addressed climate effects on crop production (Biggs et al. 2013; Knox et al. 2010; Marin et al. 2013; Sengar et al. 2014; Singels et al. 2014). Marin et al. (2013) found positive responses of sugarcane to an increase in air temperature for the State of São Paulo—the major Brazilian state producer—for all climate scenarios analyzed in the study, with gains ranging from 1% to 54% (Fig. 17.6). In general, for the range of climate projections analyzed in their study, studies concluded that the benefit of increasing temperature and CO_2 overrides the disadvantage of reducing rainfall (as projected by one of the evaluated climate scenarios) for sugarcane crops in Southern Brazil.

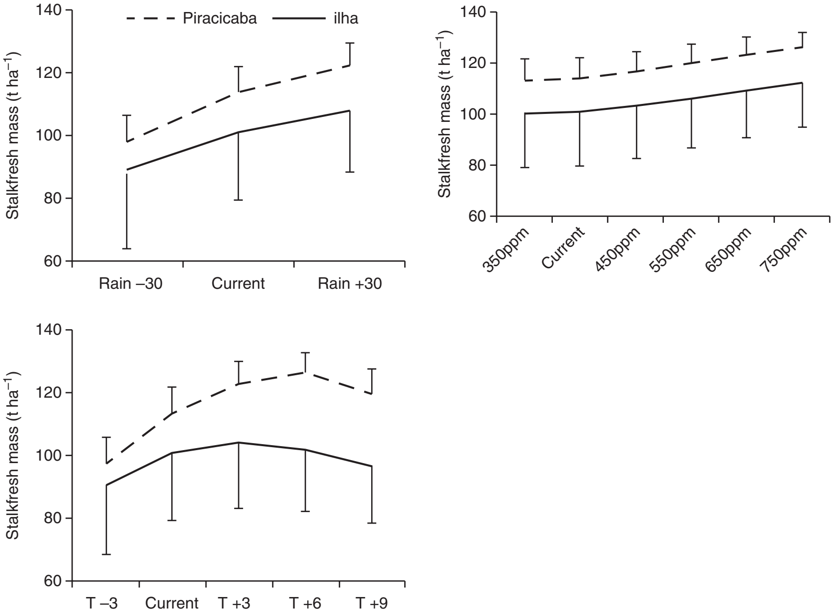

Fig. 17.6 Sensitivity of sugarcane model DSSAT/CANEGRO to rainfall, levels of CO_2 concentration, and air temperature, compared to baseline (BL), for two locations of the State of São Paulo. (Source: Marin et al. (2013). Permission – https://drive.google.com/open?id=1prgtmib0G4o17fXoG4BAZIJvNKFmsTtU)

Considering the mentioned evaluations in reference to the possible closure of yield gap and the climate change challenges for the crop, it could be expected that the sugarcane plantations in the main producing areas around the world would be able to cope with future climate, as the experimental results indicate good crop resilience to the temperature increase and the significant effect of CO_2 concentration on crop water use efficiency. For cane cultivation, the challenge would be larger toward increasing sugarcane yields on existing farmland given concerns regarding the land conversion to cane production and the possible increase of global demand for BE and sugar. Therefore, the sugarcane sector needs to improve crop production, particularly considering the following aspects:

- Breeding programs need to focus on developing genotypes able to cope with increased frequency of droughts so that marginal areas could be used to produce the crop.
- Mechanization of agricultural practices and the transition to mechanized harvest need to be accomplished.
- Push toward the transition to green harvest is necessary as this would improve soil quality and the environmental appeal of the crop-related products.
- In regions having already adopted green mechanized harvest, significant adjustments regarding the trash blanket are still required.

- Development and improvement of available systems for mechanical no-till planting will also serve as a breakthrough for reducing costs and enhancing soil quality,
- Better planning, management, prediction, and control tools are also essential for increasing input use efficiency and reducing costs for agricultural production.

R&D efforts prioritizing these areas of concern can help increase crop production without expanding sugarcane cultivation replacing other crops, pastures, and forests.

17.5 Industrial Challenges of Ethanol Production

Profitability, efficiency, and cost-benefit ratio are the major factors dictating the fate of any business. Regarding industrial production of ethanol, there is considerable room for improvement involving technological aspects. Biorefinery concept can dramatically enhance competitiveness once sugarcane sector uses all possible products and by-products to diversify its sources of profitability, utilizing the entire crop for a variety of coproducts from bagasse and molasses and incorporating them with high-value industrial plants. Hence, diversity is the key factor in today's highly integrated sugar milling operations for producing a range of products such as food, animal feed, manures, and ethanol derivatives—apart from sugar and ethanol indeed. However, many of the developing cane-producing countries are not making full use of this crop in this regard (Aguilar-Rivera et al. 2012).

Countries like Australia, Brazil, and Swaziland, for instance, have a relatively advanced and efficient industrial structure for sugarcane biorefinery agro-industrial value. Brazil has another comparative advantage as its industries are already ready to switch from sugar to ethanol or for some ratio between them depending on international prices of sugar, oil, or even the corn-based ethanol. However, in many of the sugarcane growing countries, molasses is exported. The technology used in the ethanol production is also obsolete, generating many residues such as vinasse, finding no appropriate applications and uses (Cortes-Rodríguez et al. 2018).

Another issue with industrial ethanol production from sugarcane is the low efficiency. Most of the BE were produced through first-generation technology which employs sucrose and compromises sugar production. This route can eventually lead to food × fuel issues, increasing the sugar prices (Jambo et al. 2016). On the other hand, technology for efficient ethanol production from second-generation technology is not matured, and efficient, yet. The high-cost pretreatment procedures required to digest sugarcane lignocellulosic materials before it could yield the ethanol have been a constant dilemma of the technology since its development. Second-generation production solves the biggest concern against BE engenderment, i.e., of food security; however, it will find large-scale applications only once cost-effective pretreatment options are available (Khan et al. 2017).

17.6 Challenges Related to State Policies

Sugarcane BE influences the supply chains of markets such as agriculture, industry, food, biofuel, electric power, and mainly the oil and gasoline. It is a sector that, due to the large number of stakeholders involved, needs support from the states through appropriate public policies and, in many cases, subsidies for its maintenance. Most sugar-producing countries are potential producers of sugarcane BE, but do not have the necessary governmental support for the development of this market, which is extremely important, as is the case of Brazilian ethanol production. Sugarcane BE development in Brazil, for instance, has highly relied on state policies to be able to supply the national fuel demand. The BE has been produced in Brazil since the early twentieth century but was firmly established in the late 1970s by the National Bioethanol Program (*ProAlcool*) in which the Brazilian Federal Government mandated the mixture of anhydrous BE in gasoline (blends up to 25%) and encouraged car makers to produce engines running on pure hydrated ethanol (100%). Such government support was a consequence of the first international oil crisis as Brazil targeted to reduce oil imports that were consuming one-half of the total hard currency from exports.

The Brazilian adoption of mandatory regulations to determine the amount of BE to be mixed with gasoline was also essential to the success of the program. It is one of the first steps to assure the market for companies starting to produce BE; however, it is also a challenge for the industry as during the first years, the BE costs are usually higher. In the case of Brazil, although the decision was made by the federal government during a military regime, it was well accepted by the civil society, the agricultural sector, and car manufacturers. After a period of strong growth during the 1980s, a huge sector depression was then witnessed during the 1990s with the end of government subsidies and low oil prices. Therefore, the high oil price volatility is another challenging factor that the sector needs to deal with (Goldemberg 2013).

Currently, even with the considerable incentives given by the Brazilian government in the last decades, national programs still play a role in leveraging the Brazilian sugarcane BE. The recently released program called "RenovaBio" is a Brazilian state policy created in 2017 and extended till 2030, aimed to expand the production and use of biodiesel, biomethane, and ethanol, among other biofuels, toward energy security and mitigation of greenhouse gas emissions. The establishment of national emission reduction targets for the fuel industry, in the next 10 years, together with the clean biofuel certification rates, is the main instrument created to concede credit for the BE producers (de Oliveira and Coelho 2018).

Moreover, in the United States, a national-level state policy caused the leverage of BE production. The Energy Policy Act of 2005 was one of the most significant steps toward biofuel adoption and to increase vehicles' efficiency. In addition to reducing the dependence on foreign oil sources, the inclusion of a low-carbon fuel concept requiring renewable fuels to have at least a 20% reduction in carbon emissions represented a significant contribution toward limiting the impacts of climate change (Hoekman 2009). As liquid fuels become a fundamental part of the society, their regulation also needs attention and incentives from the government. Hence, the success of BE or any new sources of fuels is highly related to government policies and commitment, as evidenced in the United States and Brazil.

17.7 Environmental Challenges of Sugarcane Ethanol Production

In the past decade, sugarcane ethanol production gained international attention after being considered as one of the most promising biofuels to mitigate the impacts of climate change in the short term (Fargione et al. 2008; Goldemberg 2007). Increasing production and utilization of BE has generated great social, economic, and environmental impacts for many tropical countries (Goldemberg 2007; Guo et al. 2015; Marin et al. 2016; Scarpare et al. 2016). The socioeconomic impacts include food and energy security, economic viability, and local prosperity—supported by the policies such as RenovaBio in Brazil (Caldarelli and Gilio 2018) and the Energy Independence and Security Act in the United States (Sissine 2007). The environmental interactions of sugarcane extend not only to reduced GHG emissions but also revolve around parameters like biodiversity, land uses, soil conservation, and the use of water resources (Filoso et al. 2015; Guo et al. 2015).

In general, the production and utilization of biofuels enhance the nation's energy security and independence, promote research and development, create job opportunities, and increase farmers' income. On the other hand, feedstock cultivation requires land, fertilizers, and other inputs and may cause additional pressure on water resources. In certain scenarios, biofuel production may emit more GHG and consume more fossil energy on an energy-equivalent basis (IPCC 2014; Haberl et al. 2013). Biofuels have direct fuel-cycle GHG emissions that are typically 30–90% lower per km travelled than those of gasoline or diesel fuels. In contrast to corn ethanol, the sugarcane ethanol system may offset 86% of CO_2 emissions from transportation sector compared to oil use, while emissions resulting from land-use change to sugarcane are paid back in just 2–8 years (Jaiswal et al. 2017). Identifying sustainable levels of bioenergy and finding ways to integrate bioenergy with food supply and ecological conservation remain a huge and pressing scientific challenge (Haberl et al. 2013). These negative impacts, however, can be minimized through careful planning, technological advances, government incentives, appropriate policies for land use, and sustainable farming inputs (IPCC 2014).

Among widely used sustainability analysis tools in the sugarcane ethanol sector, Environmental Impact Assessment (EIA) and the Bonsucro Certification are listed as two of the most popular ones (Sozinho et al. 2018). EIA is a mandatory decision support tool for environmental authorities to approve sugarcane ethanol projects, and the Bonsucro Certification is a voluntary project that aims to demonstrate the performance of the sugarcane ethanol industry (on sustainability grounds) to external stakeholders. These tools help to mainstream sustainability within the life cycle of sugarcane production and address related social and economic issues within the ethanol sector. Sustainability and environmental challenges in cane ethanol production also include ending the sugarcane burning in the fields, reducing the water use in mills, regulation of vinasse application in areas with groundwater K contamination, and the protection and restoration of riparian buffers and forest fragments in sugarcane farms.

17.8 Conclusion

Globally, the area of sugarcane is rapidly growing around the world due to increased demand of sugar and ethanol. Sugarcane is a promising crop for tropical and subtropical countries as it brings precious foreign exchange through exports and develops an entirely local subsidiary supporting agricultural, industrial, and transport operations. In the light of threats from climate change, sugarcane ethanol positions as a competitive option for reducing the world GHG emissions and, at the same time, for fostering the development of tropical non-industrialized countries through this cleaner and cost-effective source of energy. The challenges, however, are there as sugarcane prefers to grow under tropical climate, and expansion of sugarcane in most of arable lands within such climatic characteristics is limited in terms of availability and because of food × fuel issues. Yet, at locations where the production could be expanded, it is usual to verify the presence of minimal infrastructure. The slow progress of second-generation BE is also still a constraint because of high production costs. Lastly, the rapid increase of electric vehicles may also pose as a new competitor for the BE. Indeed, sugarcane BE can play a major role in the world's energy matrix; although several challenges are still posed to improve the sustainability of production and its cost-effectiveness.

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Chapter 18
Sustainability and Environmental Impacts of Sugarcane Biofuels

Suani T. Coelho and José Goldemberg

18.1 Introduction

The transportation sector represents 23% of the world's energy consumption (REN21 2017). Approximately 28% of the world's energy-related greenhouse gas (GHG) emissions originate from the use of these fuels, in addition to the majority of particulates emitted to the atmosphere, as well as sulfur and nitrate oxides – the main sources of local/regional pollution problems. Complete dependence on fuels produced from petroleum in the transportation sector creates security as well as economic concerns due to the fluctuations of the cost of petroleum. Therefore, the search for alternative fuels or electricity-driven vehicles is of great importance and has been pursued since the beginning of the twentieth century when internal combustion motors were developed.

One of such options is ethanol from sugarcane, which is a high octane clean fuel produced in large scale in Brazil since 1975. More than 100 countries produce sugarcane for sugar. The top five sugar producers, in 2016, were Brazil, India, China, Thailand, and Pakistan with 1721, 361, 124, 98, and 58 million metric tons of cane production, respectively. In the same year, the production of sugarcane ethanol reached 34.5 billion liters (L), of which 27.0 billion L were produced in Brazil, 3.2 billion L in Thailand (both sugarcane and cassava), 0.9 billion L in

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Argentina, 0.9 billion L in India, 0.4 billion L in Colombia, and 0.1 billion L in Indonesia, followed by some African countries' initiatives for the same (REN21 2017). In fact, it is surprising that only a few countries have embarked in ethanol production, despite the adoptions of mandate for a percentage of ethanol in gasoline – in general 10%, except in Brazil and Paraguay, where it has reached 27.5% or is used as pure ethanol in flex-fuel engines.

The production of sugar in Brazil uses approximately 5 Mha (million hectares) of land, and another 5 Mha are used for ethanol production. It is clear, therefore, that Brazil's experience in producing ethanol is a good testing ground for much larger production of ethanol in other sugar-producing countries. Jaiswal et al. (2017) have conducted a recent study indicating that the Brazilian sugarcane production could reach 3.63–12.77 million barrels of oil by 2045 while protecting forests under conservation. The authors conclude that it is possible to guarantee future land demand for food, with production in an area of 37.5–116 Mha up from roughly 5 Mha in use at present.

According to the "Global Agro-Economic Zones," developed by the Food and Agriculture Organization of the United Nations (FAO) in conjunction with IIASA (International Institute for Applied Systems Analysis), sub-Saharan Africa, Latin America, and Caribbean regions have the greatest potential for production of agricultural residues (Fischer et al. 2008; Smeets et al. 2007). Besides that, mentioned regions also show great aptitude for the cultivation of rain-fed sugarcane.

Goldemberg et al. (2017) have discussed in detail the situation of ethanol-producing countries worldwide. Among developed countries, the United States is the major ethanol producer (58 billion L of ethanol engendered from corn), followed by the European Union (3.4 billion L). Among developing countries, ethanol producers are mostly sugarcane-growing countries, Brazil being on the top. Moreover, China is also producing 3.2 billion L of corn ethanol (REN21 2017). African countries starting to produce sugarcane ethanol include Uganda, Sudan, Rwanda, Malawi, and Angola. Other countries such as South Africa and Mozambique have not yet started to produce ethanol, despite existing strategies already defined by the government.

In Colombia, despite lower cane crushing in 2016, ethanol production remained practically unchanged. A new distillery managed by ECOPETROL was started in early 2017, with a capacity of 500,000 L day^{-1}, bringing Colombia's total ethanol production capacity to around 565 million L per annum (Goldemberg et al. 2013). Regarding Argentina (Goldemberg et al. 2017), the government published a decree recently raising the minimum blend obligation for fuel ethanol from 10% in volume to 12% v/v. For 2017, Argentina's government planned to increase the ethanol blend to a range of 18–22%; their aim is to reach 26% blend in the future. Beyond that, Argentina is also planning to introduce the flex-fuel cars in the country in the near future.

In Asia, India and Thailand are the major countries producing sugarcane ethanol, as Indonesia has stopped fuel ethanol production. However, ethanol production faces some local concerns in India, as it could be used as a beverage. Therefore, industrial ethanol is denatured by adding unpleasant or poisonous substances (Ethanol India 2018). In 2012, the Indian Cabinet Committee on Economic Affairs decided on mandatory mixing of 5% ethanol in gasoline. India was expected to have a blend of 20% all over the country in 2017. However, the ethanol production in 2016 was only 0.7 billion L, extremely lower than the estimates, expected to increase to 1.4 billion L in 2018 (Reuters 2017).

Thailand produced 1.4 billion liters of ethanol in 2017 using 933 million tons of sugarcane, 3753 million tons of molasses, and 3193 million tons of cassava. The government had a target to increase ethanol consumption from 1.18 billion liters in 2015 to 4.1 billion liters by 2036, from sugarcane molasses and cassava. However, it is expected to lower the ethanol consumption target to 2.6 billion liters, down by 37 percent from the initial target of 4.1 billion liters, due to uncertainties about the increase in domestic production of molasses and cassava in the future, the primary feedstocks for ethanol engenderment (United States Department of Agriculture [USDA] 2017). Regarding Indonesia, the most important biofuel is biodiesel. Industrial ethanol has been produced in the country, and its production annually grew by 3 percent from 2006 to 2010; however, since then, the ethanol production ceased in the country because of disagreement in market price index formulation between the Ministry of Energy and the fuel ethanol producers (GBEP 2014b).

In African countries, encouraging initiatives have been taken in recent past. Uganda formulated its Renewable Energy Policy in May 2008. Despite the fact that Ugandan Renewable Energy Policy supports the blending of biofuels by up to 20%, the legal framework required for ethanol blending to happen in Uganda has yet to be set in place. The cabinet approved the Biofuels Bill in June 2015. Uganda produced 3.7 million tons of sugarcane in 2016. The largest molasses ethanol plant of the country has a capacity of 20 million L per year (Bioenergy International 2017).

Sudan, with 5.5 million tons of sugarcane harvested in 2016, also operates a sugarcane ethanol plant. The unit was started in 2009 with a capacity of 200,000 L day^{-1} of ethanol from sugarcane molasses. However, only 10% of ethanol is destined for domestic consumption, whereas 90% is exported to EU (Ahmed 2014). Malawi, with its 2.9 million tons of sugarcane in 2016, is also an exporter of ethanol. It yields 18.5 million L of ethanol in 2015 (Sapp 2018). In Rwanda (0.9 million tons of sugarcane in 2016), Mauritian investors are preparing to build a sugar mill having 100,000 metric tons per year crushing capacity that would also produce ethanol from molasses and electricity from bagasse (Sapp 2017). Moreover, Angola also produced 5.5 million tons of sugarcane in 2016, whereas the Angolan Bioenergy Company (Companhia de Bioenergia de Angola – Biocom) planned to produce 73,000 tons of sugar, 17,000 m^3 of ethanol, and 200 GWh of electricity in 2017 (Macau Hub 2017).

South Africa is an important sugar and sugarcane producer (15,074,610 tons of sugarcane), and it is estimated to have a potential of 400 million L of sugarcane ethanol, corresponding to a possible 2% blend with gasoline. South Africa's Biofuels Industrial Strategy, approved in 2007, concluded that bioethanol production would be financially viable at an average of US$102 per barrel (bbl) until 2015, based on estimates that producers typically pay the equivalent of US$67 bbl^{-1} for sugarcane feedstock. Less than 65% of South Africa's total liquid fuel consumption and 14% of the country's total energy consumption are derived from imported crude oil.

These imports are from OPEC countries, with about half imported from Saudi Arabia followed by Nigeria (24%), Angola (14%), Ghana (5%), and small volumes from various producers (7%) (Kohler 2016). However, Kohler (2016) concluded that the main constraint was related to the lack of regulatory policy, retarding the commercial production of biofuels in South Africa. Indeed, it is highlighted that no commercial biofuel plants have been established since the introduction of the country's Biofuels Industrial Strategy.

Tanzania, with 3.0 million tons of sugarcane produced in 2016, has suitable climate conditions and available arable land and water (FAO 2010). In 2009, a Biofuels Taskforce elaborated the Biofuels Policy and Biofuels Guidelines, addressing key issues related to institutional framework, application procedures for investors, land acquisition and use, contract farming, sustainability of bioenergy development, avoidance of food versus fuel conflicts, and sufficient value creation for the local rural population. Biofuels Policy aimed at replacing fossil fuels and stimulating socioeconomic development through rural electrification. The expected benefits also included increasing energy security, decreasing oil imports, providing alternative market for farmers, promoting job creation, and income generation. In 2015, Bagamoyo EcoEnergy Project (Tanzania Invest 2018) aimed at developing sugarcane modern crops and an industrial facility to process 1.0 million tons of cane year^{-1}, producing 125,000 t year^{-1} of sugar, 8.0 million L year^{-1} of ethanol, and 100 GWh year^{-1} of electricity to be exported to the national grid (Goldemberg et al. 2017).

Mozambique produced 2.7 million tons of sugarcane in the year 2016. The country approved the National Biofuels Policy and Strategy (NBPS) in 2009; the regulation of the production, processing, distribution, definition of percentages of mixtures, and marketing of liquid biofuels was published in 2011, demanding obligatory blends in 2012. NBPS aimed to augment international and regional cooperation, increase exports, and promote the involvement of local education and scientific society in research and development activities. This norm also stated that the exports of biofuels would only be allowed once the internal market supply is guaranteed. In 2010, there were three sugarcane ethanol projects approved by Mozambique's government and five projects proposed. Nevertheless, the climate on the global financial markets worsened in 2008 until 2009 (Schut et al. 2010). Many biofuel operators in Mozambique faced bankruptcy, and several projects were abandoned by investors, leaving behind deforested areas and unemployed workers. The legislation establishing prices has not yet been approved. The government is also developing a framework to guarantee social and environmentally sustainable production aiming to comply with EU RED as well as the Southern African Development Community (SADC). Presently, the Mozambican sugar industry consists of four factories, located in the Center and South area. Two units are installed at Sofala Province, approximately 1500 km from the capital Maputo; the other two are closer, circa 150 km, at Maputo Province (Mitchell 2011; Schut et al. 2010).

It is evident that several countries have been investing in the development of ethanol biofuel industry, some for local consumption – mostly aiming to reduce the dependence on imported fossil fuels – and others targeting external markets.

Worldwide, different stages of development are reported, from already established commercial scale programs to preliminary stages of policy and regulatory framework formation.

The analysis of the sustainability of ethanol production in its three components – economic, environmental, and social – can allow drawing important lessons for ethanol-producing countries. In this chapter, the authors present a detailed analysis of the main sustainability indicators – environmental, social, and economic indicators – based on existing literature, mainly GBEP (Global Bioenergy Partnership) publications (Almada 2017; GBEP 2014a, b, International Energy Agency [IEA] and FAO 2017; Universidad Nacional de San Martín [UNSAM] 2015), and through personal experiences and field visits in Brazil and worldwide. A general overview of sustainability aspects of sugarcane ethanol is presented, with a focus on some of the experiences of selected countries, in particular those that have already implemented the GBEP sustainability indicators for sugarcane ethanol – Argentina (Almada 2017; UNSAM 2015), Brazil (partially developed by Brazilian Reference Center on Biomass [CENBIO] 2013), and Colombia (GBEP 2014a). Some preliminary information is also included for Paraguay (Vargas 2017) and Vietnam (Quang Ha 2017) which are nowadays developing these indicators.

18.2 Sustainability Aspects of Sugarcane Ethanol

Sustainability aspects of biofuels include environmental, social, and economic impacts, both for agricultural and industrial phases of the biofuel production. Therefore, it is important to consider that these impacts, including the scenario of soil, water, and other resources, vary from country to country. In this regard, Brazil, since the *ProAlcool* Program's launch in 1975 (Cortez 2016), has achieved significant improvements on sustainability aspects. Further, other countries like Colombia and Argentina, with significant ethanol production, and referred here quite often, have also attained substantial improvements. However, as said earlier, the situation can be different in some other countries, including the nations that are only sugar producers.

The case of African countries deserves some specific comments. As mentioned by the International Renewable Energy Agency (IRENA 2016), "sustainable biofuels have an important role to play in Africa's development. Sugarcane bioethanol is currently the most cost-effective commercial biofuel and has the highest energy balance. The bioethanol industry, like sugar production, has matured in technological terms. Yet, processes could be optimized and productivity further improved, with more efficient use of energy and other resources."

IRENA (2016) analyzes that sugarcane ethanol offers several benefits for African countries, including "the increase in crop yield rates for sugarcane, small rural farmer integration into the supply chain, cogeneration opportunities using bagasse," contributing to increase energy access, and ethanol use as a cooking fuel replacing traditional biomass. Moreover, the study considers that "sugarcane ethanol production technologies are mature and well proven compared to other feedstock options and can thus offer a real economic opportunity for many African countries." However, despite the fact that these industries are quite mature, "there are challenges relating to land tenure and use, food security, agricultural practices and productivity, environmental risks, infrastructure, institutional policies and fuel quality and standards for international trade."

Aiming to discuss all these issues related to sugarcane biofuel sustainability, this section is divided into three main subsections, discussing environmental, social, and economic sustainability of sugarcane ethanol in different countries.

18.2.1 Environmental Sustainability of Sugarcane Ethanol

18.2.1.1 Greenhouse Gas Emissions Avoided by Gasoline Replacement by Biofuels

In any bioenergy process of production and use, when bioenergy is produced in a sustainable way, the photosynthesis process of the plant growth absorbs carbon emissions from the combustion of biofuels, as discussed in Goldemberg et al. (2008a, b, 2017), among others. Moreover, since carbon emissions are a global process (and responsible for the climate change), all carbon emissions must be taken into account considering the whole biofuel production process (agricultural and industrial phases). The eventual consumption of fossil fuels in the industrial phase contributes to reduce both the energy balance and the GHG emissions avoided.

In the production process of sugarcane ethanol – differently of ethanol from other crops – all energy needs for the industrial process (thermal, mechanical, and electrical) can be supplied by the sugarcane bagasse burned in the boilers. This means that the only carbon emissions come from diesel oil consumption in agricultural operations and transportation and from fertilizer use. Consequently, energy balance of sugarcane ethanol is higher than other options, and its carbon emissions avoided when sugarcane ethanol replaces gasoline are also high. In Argentina, carbon emissions avoided with ethanol replacing gasoline is 62–64% (UNSAM 2015); in Brazil, emissions avoided reach 89%; in Colombia, 54–74% (GBEP 2014a); and in Uruguay, 65% (Hernandéz et al. 2017). These avoided emissions are higher than those avoided when using ethanol from other crops, as shown in Table 18.1. For example, recent results for carbon emissions avoided with cassava ethanol replacing gasoline in Vietnam indicate values of 59% (Quang Ha 2017).

In African countries, GHG emissions have been evaluated only for Malawi. Dunkelberg et al. (2014) evaluated that, under existing production conditions, ethanol produced in Malawi leads to GHG emissions expressed as CO_{2eq} of 116 g MJ^{-1} of ethanol. Table 18.1 shows interesting results to be used when choosing the best crop for ethanol production, but local conditions must be considered as well. Soil, climate, and economic conditions are important.

Table 18.1 Avoided carbon emissions by gasoline replacement by ethanol from different crops

Crops for ethanol	Avoided emissions (%)
Sugarcane	62–89
Cassava (manioc)	59–63
Corn	−30–38
Wheat	19–47
Sugar beet	35–56
Lignocellulosic residues[a]	66.5–73

Sources: Dai et al. (2006); EBAMM (2005); IEA (2004); Macedo et al. (2008); Nguyen et al. (2007); UNSAM (2015); Quang Ha (2017)

[a] Theoretical estimates

18.2.1.2 Water Quality and Water Consumption

Water Quality Water quality and water pollution depend mainly on the adequate disposal of by-products. One of the most important issues related to water pollution in the sugarcane industry is the adequate disposal of vinasse. Vinasse is a black liquid derived from distillation and fermentation; this by-product is rich in organic matter with an acidic pH (4–5). It is a potential pollutant to water because of its composition and high temperature. Therefore, it cannot be discharged directly on rivers, and in some countries, like Brazil, the environmental legislation does not allow it.

In the beginning of the Brazilian ethanol program (*ProAlcool*), there was no control on vinasse disposal from the mills, and, in most cases, it was disposed in rivers, resulting in high pollution. The solution to dispose this by-product was found with the vinasse recycling and its use in ferti-irrigation (Souza et al. 2015). For some time it was used for this ferti-irrigation but without control. However, the impacts related to the inadequate disposal in the soil started to be significant in some cases; local studies found that the contamination of underground waters could become important when it was not adequately disposed in the crops, depending on the type of soil. Then, in 2006, the State of São Paulo Environmental Agency – CETESB – started to control the amount of vinasse disposed on soils, aiming to avoid the contamination of underground water (CETESB 2005). Nowadays, other states are also introducing the same control for licensing of the mills.

This experience is important for other countries; since vinasse is a potassium-rich product, it cannot be disposed in soils that are already potassium rich, such as those in Tucumán region, in Argentina.[1] Besides ferti-irrigation, there are other possibilities starting in some countries. In Uganda, the Kakira sugar/ethanol mill is using vinasse in a biodigestion plant to generate biogas which is later used for power production.[2]

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[1] Personal communication to authors from the University of Tucumán, Argentina.

[2] Personal visit (S.Coelho 2017).

In Brazilian mills, the vinasse biodigestion and the use of biogas for energy purposes are also starting to be considered, as in Geo Energética (Paraná), Bonfim mill, and Iracema mill (São Paulo):

- São Martinho mill, since 2010, is using biogas from vinasse for sludge drying (Globo Rural 2016).
- Geo Energética plant, near Coopcana mill, is running a patented anaerobic digestion process using vinasse, bagasse, and tops/leaves, for a 16 MW power plant since 2013 (Geo Energética [GEO] 2016).
- Bonfim mill, from Raízen Group, signed a contract to sell 20.9 MW produced from a vinasse-based biogas power plant, for a delivery starting in 2021 (RAIZEN 2016).

In some cases, the use of vinasse for ferti-irrigation is not possible, like in the Tucumán Province, in Argentina, as mentioned above. Since in this region the soil potassium content is very high, vinasse disposal in the soil for ferti-irrigation is not possible. Because of that, in the recent past, mills discharged the vinasse in rivers, producing strong environmental impacts. Recently, a new environmental legislation is being introduced, and other uses for vinasse, such as incineration, are being investigated (UNSAM 2015). In Paraguay, there are initiatives for vinasse concentration, aiming to reduce the impacts of inadequate ferti-irrigation in the underground waters, as happening in Piribebuy (GBEP Working Group on Capacity Building for Sustainable Bioenergy 2016).

Regarding other controls, one important issue is to guarantee the conservation of riparian forests nearby sugarcane (and other) crops. In Brazil, the Federal Forest Code does not allow the deforestation of riparian forests and requires the reforestation of such areas with native forests. In fact, this Code only forbids jeopardizing the growing (or regrowing) of riparian forests. Riparian forest conservation is an important issue in any country, since it protects the quality of water in rivers. However, there is no information available on this issue in other countries by now.

These experiences are interesting to be used in other countries, contributing to increase local sustainability of sugarcane biofuels. As stated by IRENA (2016), "environmental impact assessments are important on biofuel projects but several options are available to reduce negative environmental impacts. High conservation areas should not only be identified but also carefully preserved. This can be achieved by ensuring that options are available to compensate for or reduce biodiversity loss."

Water Consumption The sugarcane growth requires large quantities of water; when it is rain-fed, it requires significant rainfall, in the range of 1500–2500 mm a year, ideally spread uniformly across the growing cycle.

In many countries, sugarcane must be irrigated since rainfall is not enough. For instance, African countries need irrigation for sugarcane crops (sugar producers), but in most cases there are no funds available for that. IRENA (2016) analyzes the case of African countries as: "sugarcane cultivation requires considerable amounts of water even in areas where sugarcane is not irrigated. Water rights and allocation schemes in Africa are complex due to seasonal variation and there are disputes over the size of flows needed to preserve specific environmental measurements."

In Colombia, sugarcane crops are irrigated as well, and the total water consumption in ethanol process in the country is quite high, viz., 20–75 m^3 tc^{-1}[3] (GBEP 2014a). The cases of Brazil and Argentina are different. Most sugarcane crops in North Argentina are rain fed (without ferti-irrigation), but industrial consumption of water is still high, i.e., 17.5 m^3 t^{-1} of ethanol, according to UNSAM (2015), corresponding to around 1.2 m^3 tc^{-1}.[4] In Brazil, most of the sugarcane production (80% of the cane produced in the country) relies on rainfall, rather than irrigation, including nearly the entire São Paulo State sugarcane-producing region which accounts for 60% of cane production. NE semiarid region, on the other hand, relies mostly on irrigation, due to the lack of adequate rainfall. In South-Center, cane fields are rain fed, and complementary ferti-irrigation is through vinasse and recycled water from sugarcane processing, as in 98.4% of the cane plantations, according to ANA (2017).

Brazilian ethanol industrial production used large amounts of water in the past. Recently, there has been a significant reduction on water consumption in the milling process. In 2005, mills reduced this amount from 5.0 to 1.2 m^3 t^{-1} cane from which 87% is used in the processes inside the plant. In 2013, in some mills in São Paulo State, this figure was less than 0.7 m^3 t^{-1} cane.[5] This shows that water consumption has substantially decline in recent years. Most of the water used is being recycled, and a dry washing process (with air) is replacing the standard wet washing process. In the case of São Paulo State, the introduction of the mechanical harvesting of green cane allowed the sugarcane to be quite clean. If necessary, additional cleaning systems include only dry cleaning with compressed air. This process, together with other initiatives for limiting water usage, allowed huge water consumption reduction in the industrial process.

On the other hand, in countries where sugarcane is harvested manually (both burnt cane or green cane manually harvested as in sub-Saharan Africa), the cane presents many impurities and requires additional washing, which increases water consumption.

18.2.1.3 Land Availability

When discussing biofuel sustainability, several concerns related to the conservation of native forests and other important biomes are always presented; some studies even consider that any bioenergy crop comes from deforestation (Fargione et al. 2008; Searchinger et al. 2008; World Bank 2008). Notwithstanding, these studies only consider the worst case, which is not currently occurring, since biofuel production in general is not expanding into pristine tropical forests. Existing extensive studies evaluating CO_2 releases from agricultural practices that do not involve

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[3] tc = metric tons of cane.

[4] Authors' calculation based on 80 L of ethanol per tc.

[5] Authors' personal visit in sugar mills.

deforestation show results to be less alarming (Cerri et al. 2007). However, other studies (e.g., Goldemberg et al. 2008a, b and 2017) show that bioenergy crops are being expanded in pasturelands without any deforestation.

In Africa, according to IRENA (2016), about 10,000 hectares for bioethanol production in two countries, Swaziland and Malawi, would represent 5% and 0.6%, respectively, of the actual arable land. The study informs that their current arable land amounts to 1.2% and 0.1% of potential arable land. Both countries have sugarcane plantations of 52,000 and 23,000 hectares, corresponding to 27% and 1.3% of current arable land, respectively. They are among the lowest-cost sugar producers in the world. IRENA (2016) concludes that, assuming land requirement is not really a major concern for these small countries, producing sugarcane at a lower cost could give them some advantages if they produce bioethanol. The study also analyzes the current arable land in 17 countries against the potential arable land in sub-Saharan Africa in 2012. As shown in Fig. 18.1, 11 of the 17 countries analyzed have a land use rate below 25%, with a significant potential for agricultural expansion.

In fact, this is a quite controversial issue, and here, some general figures are presented and discussed. According to Souza et al. (2015), estimates for land demand for modern bioenergy are in a large range, 50–200 Mha by 2050, which correspond to 44–135 EJ year^{-1} of modern bioenergy in 2050. The authors consider approximately 0.7 EJ per Mha as a reasonable land use intensity for the production of modern bioenergy at this scale in the 2050 timeframe. The same study comments that there is 1.4 Bha of "prime and good land" available for rain-fed agriculture and further 1.5 Bha of marginal land that can be considered "spare and usable." Around

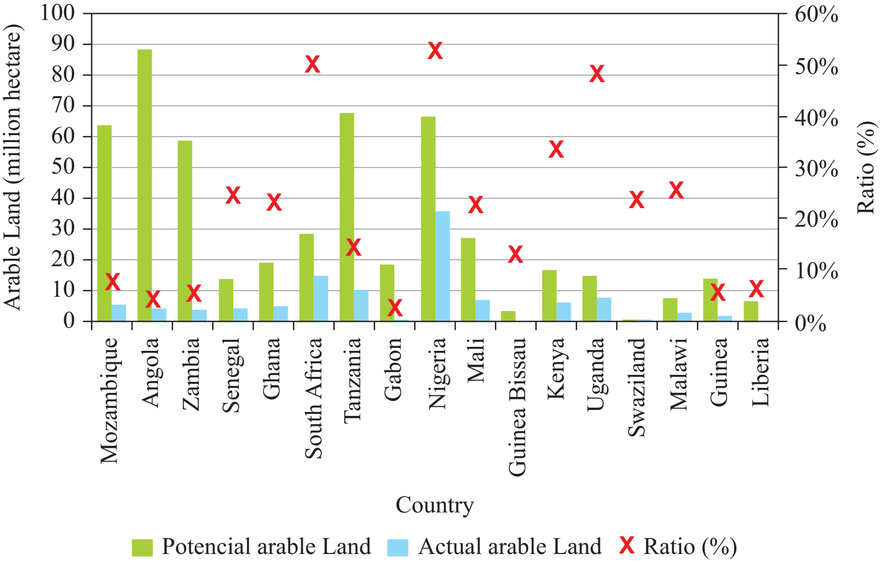

Fig. 18.1 Ratio between actual arable land and potential arable land in sub-Saharan Africa. (Source: IRENA 2016)

960 Mha of this land is in developing countries in sub-Saharan Africa (450 Mha) and Latin America (360 Mha) with most of it currently under pasture/rangeland.

In 2016, the land availability for agriculture in Brazil continued to be 355 Mha, from which 24.7% is being used for agricultural purposes and the area occupied by sugarcane accounted only for 2.8% (around half of this destined for ethanol production). Moreover, 39% of the country area corresponded to available land, and 48% was occupied by pastureland (productive and degraded). This means that there is the possibility of expansion of agricultural crops, as already occurred in the State of São Paulo, through the replacement of pastures, which have become more intensive (Escobar 2016). In 2001, in the State of São Paulo, the average number of cattle heads per hectare was 1.28. As of 2008, it had increased to 1.56 because of the expanding sugarcane plantations pressuring cattle grazing. Overall in the country, the density is even lower, i.e., close to one head per hectare (Goldemberg et al. 2008a, b; Lora et al. 2006).

In fact, the Brazilian sugarcane crop expansion is concentrated in the Center-South production region that does not encompass the important biome-producing areas – Amazon Rainforest, Atlantic Forest, and Pantanal (Smeets et al. 2006). As of 2016, Brazil had approximately 215 million heads of cattle on 168 Mha (GTPS 2017). If these cattle could grow in a more intensive way, reaching 1.5 heads per hectare,[6] the country could have around 60 Mha available as shown by the Brazilian Agricultural Research Corporation (EMBRAPA 2009) and discussed previously by Coelho et al. (2011), among others.

In Colombia, sugarcane plantations occupy 0.05% of the total area of the country and 0.12% of the agricultural area. In the country, cattle are spread in 40 Mha, out of the total 111 Mha of the country (GBEP 2014a). In Argentina, biofuels occupy an area corresponding to 2% of the country, and sugarcane expansion has been mainly over areas planted with soy or used for pasture (UNSAM 2015).

Worldwide, as Souza et al. (2015) analyzed, the possible increase of animal stocking densities to currently attainable climate appropriate levels – such as in the case of Brazil – could allow existing pastureland to support 3.8-fold more animals. Bringing the poorest-performing pastures up to 50% of their maximum attainable density would more than double the global stock of grazing animals. Gross estimates of the potential for energy crops on possible surplus good quality agricultural and pasturelands range from 140 to 290 EJ y^{-1}.

In addition, recent studies have analyzed Indirect Land Use Changes (iLUC), showing that there is no concrete evidence that sugarcane crop expansion is producing deforestation. These studies allowed that the US Environmental Protection Agency (EPA) recognized that sugarcane ethanol indeed reduces carbon emissions (Nassar et al. 2009). Recent studies present that, in the context of climate change mitigation, updated models estimated lower values for iLUC. Such models allowed a revision of the initial GHG estimates from 111 to 13.9 g $CO_{2\,e}$/MJ for sugarcane, almost a tenfold decrease. On the other hand, the emission factor of gasoline is 92 $CO_{2\,e}$/MJ (Souza et al. 2015).

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[6] Important to note that1.5 head/hectare is not considered an intensive growth.

Regarding land issues, one major question is that of land tenure, mainly in African countries. As discussed in IRENA (2016), land tenure in Africa is a complex matter, varying from country to country; most African countries have a dual system for land tenure, including both the "modern," i.e., market-oriented system, and the "traditional" land tenure system, in which local chiefs are responsible for land allocation. These two parallel systems are sometimes in conflict, especially in terms of international investment. This may produce some uncertainty among investors and sometimes may make investments difficult, weakening the ability of the local community to negotiate long-term leases in a proper way. In this context, IRENA (2016) recommends: "land laws need to be reinforced to protect local people and ensure security of land ownership while also promoting the transparent allocation of land for biofuels."

Due to concerns related to land availability, among other environmental impacts, second-generation ethanol has been considered a better option compared to the conventional process of first-generation. The use of cellulosic residues to produce ethanol is seen as an option to make more land available for food production. However, the development of second-generation biofuels did not follow the progress as expected, mainly in developing countries. Brazil, leader of sugarcane ethanol production using first-generation, has started with two plants: one in Alagoas (GRANBIO) and the second one in São Paulo (Costa Pinto mill, Raízen Group). The second-generation (2G) ethanol plant in Alagoas faced significant technological difficulties and decided to halt this process and to use the available biomass for cogeneration (Guadagnin 2016); thus, only the Raizen pilot plant continues the activity.

18.2.1.4 Soil Quality

Soil quality is an important issue worldwide; however, it has great importance in reference to African countries especially. In semiarid regions, such as in sub-Saharan countries, soil quality significantly impacts agricultural productivity, as discussed ahead.

In Brazil, sugarcane culture has become more sustainable over the years as the sugar mills introduced some practices ensuring the appropriate use of fertilizers and soil protection against erosion, soil compaction, and moisture loss. Some soils have been producing sugarcane for more than 200 years in the country, with no yield reduction. In fact, agricultural production has increased significantly. Sugarcane culture, in Brazil, is well known for its relatively small loss of soil to erosion, especially when compared to soybeans and corn.

Nowadays, with the introduction of the green harvesting of sugarcane, a significant debate is on the way related to the amount of residues to be left in the field to protect soil. Studies from EMBRAPA (2017) show the importance of sugarcane residues left in the soil as they protect the soil and allow the infiltration of water in the soil and reduce erosion, among other benefits. A recent study concluded that on average 50% of tops and leaves must remain in the soil after the mechanical harvesting (Otto et al. 2017). In this regard, Mello et al. (2014) mention "the positive impacts on soil quality following the replacement of pastures by sugarcane crops: results demonstrate that soil C stocks decrease following LUC from native vegetation and pastures, and increase where cropland is converted to sugarcane."

18.2.1.5 Agrochemicals

Sugarcane crops require the use of many inorganic compounds, including chemicals to kill weeds, insects, mites, and fungi, along with defoliants and other chemicals that help the cane to mature more quickly. Concerning agrochemicals, the amount of agrochemicals used in sugarcane production is lower than the one for other crops such as corn. Pesticide consumption per hectare for sugarcane is also lower than for citrus, corn, coffee, and soybeans. Nevertheless, sugarcane requires more herbicides per hectare than coffee but still less than do citrus, corn, and soybean. Furthermore, sugarcane uses smaller amounts of fertilizer than cotton, coffee, and oranges, and about the same amount as soybeans (Macedo 2005). One practice regarding sugarcane that helps here is using industrial waste as fertilizer, especially the vinasse. This has led to a significant increase in productivity and in the potassium content of the soil in Brazil (Ripoli et al. 2005).

Genetic research, especially the selection of resistant varieties, has made it possible to reduce the diseases affecting sugarcane, such as the mosaic virus, the sugarcane smut and rust, and the sugarcane yellow leaf virus. Plants with genetic modifications have more resistance to herbicides, fungus, and the sugarcane beetle, some of such transgenics are already being field- tested. At present, there are more than 500 commercial varieties of sugarcane available in spite of the fact that about 60% of the planted area relies on eight varieties in Brazil. This experience is important to avoid major losses in the event of an epidemic disease. It is important for other sugarcane producer countries, including those producing only sugar from sugarcane.

As discussed in IRENA (2016), the demand for agricultural inputs, such as fertilizers, machines, and services, will increase yield and reduce the vulnerability of small farmers, apart from improving the food security. This means that the progress achieved from the agricultural phase of ethanol production can also be used for the sugar production since in both cases the agricultural phase for sugarcane production is the same.

18.2.1.6 Air Pollution

Besides the environmental advantages of sugarcane ethanol replacing gasoline in engines, with reduction of most of the pollutant emissions (mainly CO_2, SO_x, and particulates/PM), atmospheric emissions in sugarcane ethanol production must also be addressed. In this area, there are two issues to be considered: atmospheric emissions from sugarcane burning before harvesting and those from bagasse burnt in boilers for cogeneration.

Several countries still use the manual harvesting of both burned and green cane. Green cane manual harvest is possible, but the celluloid leaves can hurt if no protection equipment is used, and there is a high risk of accidents with poisonous snakes and spiders (Ripoli et al. 2005). Sub-Saharan countries use manual harvesting of green cane despite all the risks for the workers. Argentina and Colombia use the burning of sugarcane crops before harvesting, but legislations are changing (GBEP 2014a; UNSAM 2015). In Argentina in the Tucumán Province, Law 6253/2005 started to eliminate the burning of sugarcane (UNSAM 2015).

The African situation deserves specific discussion. Based on the Brazilian experience and as discussed in IRENA (2016), we can conclude that sugarcane mechanization can indeed improve productivity and (in the long term) reduce costs, as it has happened in São Paulo State with the introduction of green sugarcane mechanical harvest. The elimination of sugarcane burning has strong positive environmental benefits due to the huge pollutant emissions avoided. On the other hand, manual labor offers economic advantages, mainly for African countries, due to job creation in rural areas, which is important in the African context. In this subject, the Brazilian experience of capacity building of the former cane cutting workers is important. In addition, IRENA (2016) analyzes that "if irrigation infrastructure and mechanized harvesting are provided by the collaborating industry, the involvement of out growers or block farms may be feasible, as is common in Tanzania."

From the Brazilian experience, it is known that the burning of sugarcane damages the tissue of sugarcane, disturbing the soil structure and enhancing the possibility of soil erosion (Ripoli et al. 2005). Besides, there are huge pollutant emissions, such as particulate matter, carbon monoxide (CO), and methane (CH_4); locally it can increase the tropospheric ozone concentration. Yet, there are several implications to the industrial phase like difficulties on sugarcane cleaning and the need for faster utilization of feedstocks due to the shorter period for exteriorization (CENBIO 2006).

In Brazil, the current situation is different. The first environmental legislation establishing to phase out sugarcane burning in the State of São Paulo was introduced in 2002, through State Law 11 241, from 19 September 2002. Further, the so-called Green Protocol has been signed as well in 2007,[7] and, since January 2018, 100% of the sugarcane in the state was to be green mechanical harvested. In many other states, the local environmental agencies are also requiring the harvesting of green cane as one of the exigencies for the environmental licensing. States such as Mato Grosso, Goiás, and Mato Grosso do Sul (Center-West region) are establishing similar legislations.

The other important aspect of air pollution is the use of bagasse in boilers for the energy supply of the industrial process. This process has high advantages for the industrial productivity and for carbon emission reduction as well. Moreover, there

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[7] In December 2017, 98% of sugarcane in São Paulo State is mechanically harvested, and from January 2018, 100% will follow the same.

are also the usual pollutant emissions to be controlled. There are no sulfur emissions from burning biomass, but there are emissions of PM and NOx, for which threshold values defined by the governments exist. In Brazil, both emissions are controlled, with adequate enforcement, by the Federal Council for Environment (CONAMA 2006). Such controls should be mandatory in every country, and existing initiatives like the Cogen for Africa project (Global Environment Facility [GEF] 2007) are good examples showing how the use of more efficient technologies together with environmental concerns can improve the use of biomass.

Regarding ethanol use in vehicles, existing studies show the benefits of ethanol replacing gasoline in various countries. Salvo et al. (2017) showed the reduction on PM (nanoparticles of particulate matter) in air quality of São Paulo city when ethanol consumption is higher than gasoline. Variation of gasoline and ethanol shares among flex-fuel vehicles between January and May 2011 showed that ultrafine PM concentration increases when gasoline shares augment. For Colombia, GBEP (2014a) shows that emissions of non-GHG pollutants from E10 blends are generally lower than emissions from the use of straight gasoline (tank-to-wheel). In particular, compared to gasoline, E10 emits 17% less CO, 15% less NO_x, 16% less PM, and 34% less SO_x.

In addition, as mentioned by IRENA (2016), ethanol can replace lead, still used in African countries, which is harmful. According to IRENA (2014), the demand for transport fuels of Ethiopia, Kenya, Nigeria, and South Africa alone will amount to more than 4100 petajoules by 2030, showing significant environmental advantages of replacing lead.

18.2.2 Social Sustainability of Sugarcane Ethanol

18.2.2.1 Impact of Sugarcane Ethanol Production on Food Prices

The controversy of food × fuel has a long history in the biofuel’s pathway. The topic has been debatable with different opinions from various researchers (summarized in Souza et al. 2015).

According to IRENA (2013), as illustrated in Fig. 18.2, food prices have been increasing over the last 12 years, mainly due to high oil prices, reflecting on the energy inputs (transportation and agricultural machines) and on fertilizer prices. In addition, the demand for food was increased due to the economic growth in the period. IRENA (2013) concludes that “the growing demand for biofuels has also contributed to some extent, although analysis of this area has yet to reach agreement on the relative weight of different factors.”

More recently, IRENA (2016) states that sugar industries are already in place in most African countries, and ethanol is being produced from existing molasses stocks. Then, the expansion of sugarcane planting areas will result in more sugar. The study concludes that, depending on the scale, it is unlikely that molasses may offer a better return than bioethanol for a country importing oil. It also concludes

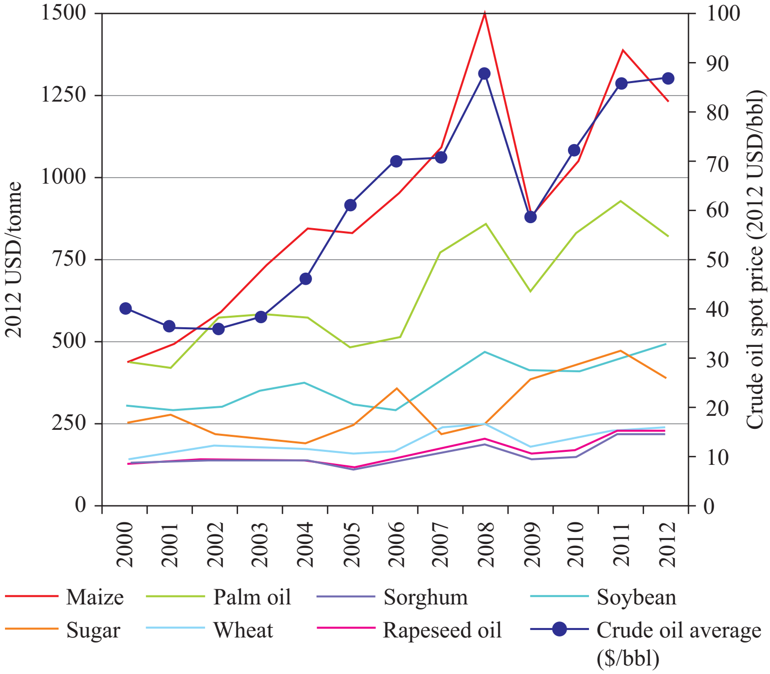

Fig. 18.2 Global prices for food-based biofuel feedstocks and crude oil (2000–2012). (Source: IRENA 2013)

that "the industry is already integrating smallholders into the supply chain (…), and this is considered a leapfrog step in the sustainable production of bioethanol. This reduces the conflict between food and fuel, and helps the African continent to be self-sufficient in sugar."

In fact, IRENA (2016) recognizes that the Brazilian experience shows that sugar production increased at the same time as the sugarcane area. Most Brazilian mills (65%) decided to have units able to produce both sugar and ethanol (limited to a 40–60% mix due to operational and economic factors). This operational flexibility allows the stabilization of sugarcane supply and reduces the risk of market volatility. In addition, recent studies from the GBEP indicators for Argentina and Colombia concluded that there is not any negative impact. This session presents the results of existing studies, including those concerning Argentina, Brazil, and Colombia,[8] as well as a general approach of this subject.

Studies for Brazil also present similar results. Caldarelli and Gilio (2018), from the analysis of a food basket in the State of São Paulo compared with the increase of sugarcane plantations, concluded that there is not any impact on food prices. Figure 18.3 illustrates the prices of a basic basket of Groceries Index in São Paulo with FAO Food Price Index (Caldarelli & Gilio 2018).

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[8] Some figures are presented for Vietnam and Uruguay as well, when available.

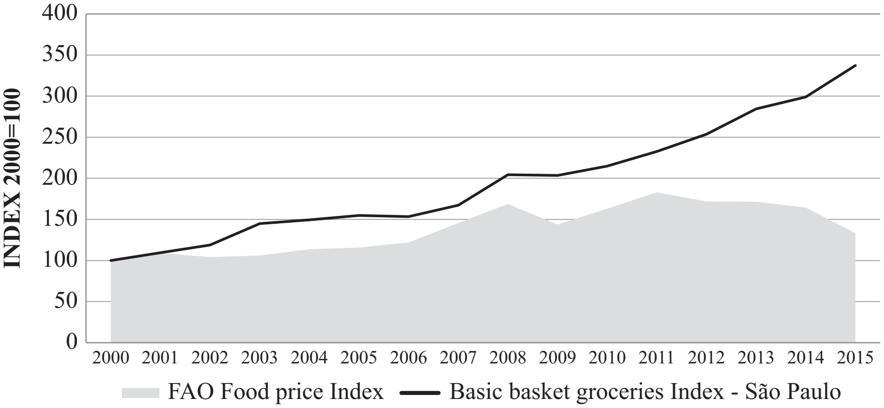

Fig. 18.3 Evolution of the basic basket of Groceries Index in São Paulo and FAO Food Price Index, 2000–2015. (Source: Caldarelli & Gilio 2018)

However, the controversy of food × fuel still exists in African countries. As discussed in IRENA (2016), "in some African countries, governments prevented biofuels deployment due to concerns about food security. However, such restraints could reduce job opportunities in rural areas and limit the income of farmers in areas often affected by poverty."

In addition, REN21 (2017) analyzes that the policy debate over the sustainability of first-generation biofuels continued in 2016, with the resurgence of the food versus fuel debate, particularly in Argentina, following the rising price of soy oil during the year. Despite ongoing debates over biofuel production and use, biofuel support policies continued to be adopted. It was assessed that biofuel blend mandates and financial backing for such blending programs were the most consistent forms of support.

As mentioned before, concerns related to sustainability and the food × fuel debate have stimulated the development of second-generation ethanol, using residues, to avoid this competition. It is also important to recall the difficulties faced by one of the plants for 2G ethanol in Alagoas, Brazil. This failure indicates that further research may be necessary to allow 2G ethanol production in developing countries and that first-generation ethanol seems to be the most viable option currently.

18.2.2.2 Number and Quality of Jobs

Around 75% of the population depend directly on agriculture in developing countries (Souza et al. 2015). Therefore, it is fundamental to increase the number and the quality of jobs for poverty reduction. There are roughly 2.7 billion people living under a budget of US$ 2.00 per day and even lower[9] and 1.0 billion people without

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[9] In sub-Saharan countries, the average payment for jobs in rural areas is $1.0 per day (authors' personal communication during field visits).

electricity (REN21 2017). At the same time, there is a great lack of adequate access to modern and clean fuels, with the subsequent dependency on traditional biomass (Goldemberg and Coelho 2013). Biofuel production may generate significant social benefits for the developing countries, like economic growth and decrease of unemployment rate for people with low years of schooling in rural areas, through creation of jobs in such areas.

In South Africa, for example, it was estimated that with the blending target of 10% in gasoline, the government could create about 125,000 direct jobs mainly in rural areas (Kohler 2016). In India, in 2016, 35,000 jobs were created in the sugarcane sector (REN21 2017). In addition, the investment needed to create these jobs is much lower in the biofuel sector than in others. In Brazil, one job position creation in ethanol agro-industry costs about US$11,000, whereas, for petrochemical industry, the cost is 20 times higher (Goldemberg 2002). There were 783,000 jobs in 2016 in this sector (REN21 2017), considering the reduction of jobs in agriculture, which decreased because of the introduction of mechanical harvesting.

Despite the benefits from sugarcane ethanol, rural field workers' condition worldwide is a subject of criticism. In fact, in many developing countries, the labor conditions in sugarcane plantations are quite inappropriate, considering the manual harvest of green sugarcane. There are negative consequences of the arduous work in sugarcane fields to health and the high risk of accidents with animals, as discussed previously in this chapter. In this context, the Brazilian experience of introducing the mechanical harvesting of green cane and the requalification programs for the workers must be taken into consideration.

Yet, looking at the Brazilian experience of sugarcane mechanical harvesting, an important question discussed in the country was the possible unemployment of rural workers with low level of education involved in the manual harvesting. Such workers would lose their jobs due to mechanical harvesting and might have difficulties to fit in the labor market. Regarding this issue, special policies were developed to tackle this problem including the qualification of rural workers through the partnership of unions. UNICA (União da Indústria Canavieira/Brazilian Sugarcane Industry Association), with associated companies, works to improve the skills and qualifications of workers. The results are interesting as 7000 workers were qualified in 1 year (UNICA 2007). Current results indicate that in 2007, in São Paulo, through the requalification program, 190 mills associated to UNICA retrained more than 22,700 people from 80,000 that had been replaced by the mechanical harvesting; 80% of those workers remained in such mills.

This experience shows that mechanical harvesting of sugarcane can be an interesting option, yet it can present challenges in the initial phase of the biofuel program. In most cases, it is vital to generate jobs in rural areas, mainly in developing countries, so the manual harvesting has its own significance. However, labor legislation regularizing manual harvesting of green cane must be mandatory, considering the extremely hard work of harvesting green cane. In the second phase of biofuel production, associated to an adequate capacity building program, mechanical harvesting can be imperative since it reduces the air pollution of the sugarcane burning.

Another important aspect of social situation in the sugarcane sector is related to the quality of jobs created. Usually the agricultural sector presents many informal jobs, where the worker is not included in the national social security system. However, regions with sugarcane production, in general, present a better social situation. Considering the example of Brazil, in 2015, almost 90% of the created careers in the sugarcane sector were formal jobs, against only 34% in other agricultural sectors. Moreover, studies indicate that in the sugarcane sector, there is a higher mobility of workers to other better jobs (Moraes et al. 2015).

Reference to wages, in South-Center production region, sugarcane workers earn more than those working in coffee, citrus, and corn sectors, but less than workers in soybean sector; since this work is highly mechanized and requires specialized workers (Goldemberg et al. 2017). In the North-East, people working in sugarcane crops earn more than those working in coffee, rice, banana, manioc (cassava) and corn crops, being their income approximately equivalent to those working in citrus, but lower than the people working for soybean. In fact, the enforcement of labor regulations in some regions of the country could be improved, aiming to achieve the same situation already existing in several sugarcane regions. Moreover, in Brazil and Colombia, the wages of sugarcane sector are quite high. In Colombia, wages of sugarcane workers are in average 2.5–4.5 times the legal minimum wage of the country (GBEP 2014a); in Brazil, wages in sugarcane are 45 % higher than in other agricultural sectors (Moraes et al. 2015).

Studies also show the positive impact of new sugarcane mills in São Paulo State municipalities. As per report of Moraes et al. (2016):

- New industrial plant installations lead to rise in average municipal GDP (annual per capita). An increase of US$1098 in the municipality where the mill is installed and US$457 in each of the 15 municipalities around such installations has been observed.
- Regarding timeline, 10 years after the mill installation in sugarcane areas, the annual municipal GDP grows. An increase of US$1028 in the municipality where the mill is installed and US$324 in each of the 15 municipalities around the mill has been reported.

From these experiences, it is clear that sugarcane biofuels have positive social and economic impacts in the regions where they were introduced. The perspectives for developing countries, mainly the least developing countries, can be quite promising, as shown in Mitchell (2011). Mitchell (2011) showed that, with the introduction of biofuel programs in Africa, wages can increase from US\$1.0 day^{-1} to US\$3.0 day^{-1}.

18.2.2.3 Bioenergy to Improve Energy Access

One of the most important social benefits from sugarcane ethanol is its contribution to the increase in energy access in developing countries, mainly in rural areas. Sugarcane mills are located in rural areas and, in the case of developing countries, can contribute to surge the rural energy access in such countries, which face huge problems on this subject (Goldemberg and Coelho 2013).

Considering the use of by-products from ethanol process (bagasse, tops and leaves, vinasse, and filter cake), there is a strong opportunity for their efficient use to generate electricity to be distributed in rural households, increasing energy access.

There are some interesting examples worldwide, such as the following:

(i) In Brazil, all sugarcane mills are self-sufficient in terms of energy since they use the sugarcane bagasse for cogeneration, and a large number of them generate surplus energy. According to Souza (2017), from the 378 Brazilian sugarcane mills, 44% (166 mills) generate energy surplus to the grid and the other 56% (212 mills) are self-sufficient. The total amount of electricity generated from sugarcane bagasse was 32.2 TWh, from which 21.1 TWh were sold to the grid, for a total sugarcane crushing of 651.8 million tons (2015/2016 season). Moreover, mills produced 38.7 million tons of sugar and 27.3 billion liters of ethanol (hydrous and anhydrous).

(ii) In sub-Saharan countries, the Cogen for Africa project (GEF 2007) is introducing efficient technologies for biomass cogeneration to produce surplus energy to be supplied to rural households. The project is now being developed in Kenya and Uganda sugar mills and tea factories.

(iii) One of the industries that benefited from the Cogen for Africa project, Kakira Sugar Industries (Kakira n.d.), in Uganda, currently produces 20 MW using the bagasse from 6000 tons of cane per day. Moreover, they have also installed a biogas from vinasse power plant (200 kW), serving the purpose of vinasse utilization.

(iv) In Brazil, ethanol mills are also becoming interested in the energetic use of vinasse. Vinasse biodigestion produces biogas that can be used both for electricity and for biomethane production[10] (from biogas upgrade process). Biomethane can be used in agricultural machines; moreover, it can also be injected into the natural gas grid. In this context, there are similar experiences in Uganda, where the biogas is used to produce electricity, and in Paraná State, in Brazil, where Geo Energética power plant uses filter cake, bagasse, and vinasse in a patented process. This plant had its start-up in 2012 with 4 MW and forecast an expansion of 16 MW (GEO 2016).

The use of sugarcane residues (bagasse and vinasse biogas) is also an extremely interesting option, considering the possibility of generating an electricity surplus to be supplied to the grid and to supply to the households in rural areas, mainly in countries with lack of energy access. In South Africa, for example, the electricity production from sugarcane bagasse is around 30 kWh tc^{-1} and could be increased up to 200 kWh tc^{-1} (Kohler 2016).

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[10] Biogas is the gas produced by the anaerobic digestion of organic matter (CO_2, CH_4, and others). Methane content is in a range of 40–60% depending on the biomass. The gas obtained from the upgrade process, eliminating CO_2 and other pollutants, is methane (then called biomethane). If this biomethane follows technical standards, it can replace natural gas in any end use.

18.2.3 Economic Sustainability of Sugarcane Ethanol

Economic sustainability of biofuels involves a large range of aspects, such as production costs (linked to biofuel productivity and to adequate tax policies), energy balance, and logistic issues, among others.

18.2.3.1 Agricultural and Industrial Productivity of Sugarcane Ethanol

Both agricultural and industrial productivity of biofuels are fundamental to allow a reduction of production costs and its economic competitiveness with fossil fuels, such as the case of ethanol × gasoline.

Regarding agricultural productivity, in Argentina, it is on average 63–66 tc ha^{-1} (UNSAM 2015), in a range of 57–93 tc ha^{-1}. In Colombia agricultural productivity is higher, since the sugarcane crops are irrigated (115.75 tc ha^{-1}, GBEP 2014a). In Thailand, it is in the range of 69–75 t ha^{-1} (USDA 2017).

In Brazil, since 1975, the agricultural productivity of sugarcane has increased from approximately 45 tons ha^{-1} to 80 tons ha^{-1} and 6000–10,000 l ha^{-1}, depending on the region. Figure 18.4 shows the agricultural productivity in different regions in Brazil in recent years according to ÚNICA (2017), where one can see the higher

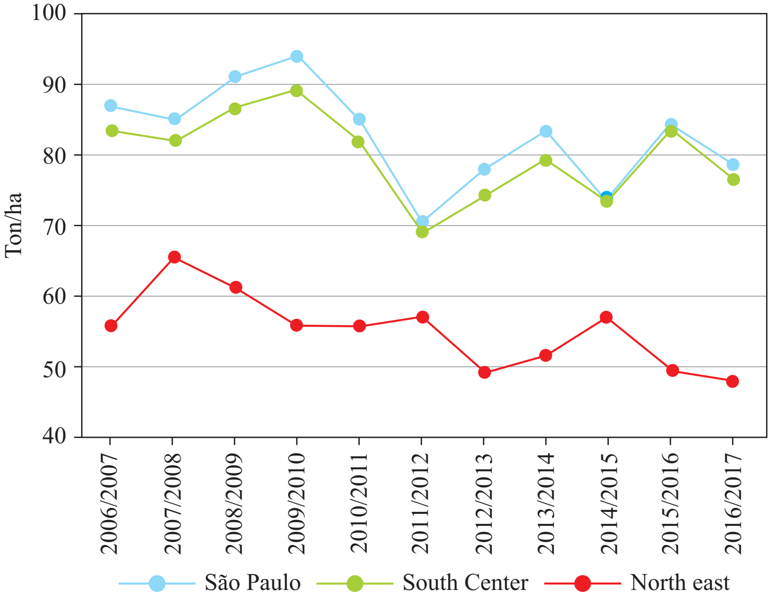

Fig. 18.4 Agricultural productivity of sugarcane in different Brazilian regions. (Source: ÚNICA (Brazilian Sugarcane Industry Association) 2017)

productivity in Center-South and São Paulo State, compared to Northeast Brazil. This is the reason why sugarcane production in NE has been reducing during the last years, corresponding now only to 7% of the country's production. In addition, ethanol production in NE is quite lower than the one in South-Central regions, as well. This lower agricultural productivity in NE Brazil is comparable to those in some other locations such as in sub-Saharan countries.[11]

In some African countries, where sugarcane crops are not irrigated, agricultural productivity can be as low as 5.6–10 tons of cane ha^{-1} (in Central African Republic or Cameroon), against Kenya (81 t ha^{-1}) and Uganda with 67 t ha^{-1} (FAO n.d.). However, industrial productivity can be quite high. In South Africa, Kohler (2016) reports that an industrial productivity of sugarcane ethanol could be 80 L tc^{-1}. Based on this, Kohler (2016) estimates the ethanol production costs in the country equal to 70 US cents L^{-1}.

Additional gains are possible as shown in Fig. 18.5, which demonstrates agricultural yield and the sugar content from 155 producing units in the Southeast of Brazil. The average agricultural production of this significant group of plants is 82 tons ha^{-1} and 12.9% of fermentable sugar content; however, a productivity of 100 tons ha^{-1} and a sugar content equal to 14.5% have already been reached in a number of plants using different types of cane, irrigation, and better management strategies.

On the other hand, when considering industrial productivity, the figures are similar in all regions, in a range of 74.10–78.01 L tc^{-1} (Companhia Nacional de Abastecimento [CONAB] 2017). This shows that in many countries industrial productivity can be the same, not depending on the geographic location but only on the industrial process. The industrial productivity (ethanol from sugarcane) in Argentina is similar to that in Brazil. Argentinian sugarcane ethanol mills have an average industrial productivity of 79.45 L tc^{-1} (UNSAM 2015). In Colombia, on the other hand, industrial productivity is lower since ethanol is produced from molasses, on average 300 MJ tc^{-1}, that corresponds to 13. L tc^{-1} (GBEP 2014a). Similarly, Thailand has an industrial productivity for sugarcane ethanol equal to 78 L tc^{-1} (USAID 2017).

IRENA (2016) discusses the issue of agricultural productivity in developing countries, analyzing that the participation of small growers in feedstock production is viewed as a way to reduce poverty, but the low agricultural yields and poor agronomic practices can harm agricultural production and biofuel development by increasing production costs. Sugarcane harvesting and delivery can be costly due to the lack of roads and adequate transportation. Authors' personal experience in sub-Saharan countries confirmed these difficulties, since the harvested sugarcane is transported by horses in many cases, losing sucrose and reducing industrial productivity. Therefore, it is evident that better logistics and coordination can help in lessening the production costs and can benefit the industry (IRENA 2016).

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[11] Personal communication. Authors' visit to sub-Saharan countries, 2011.

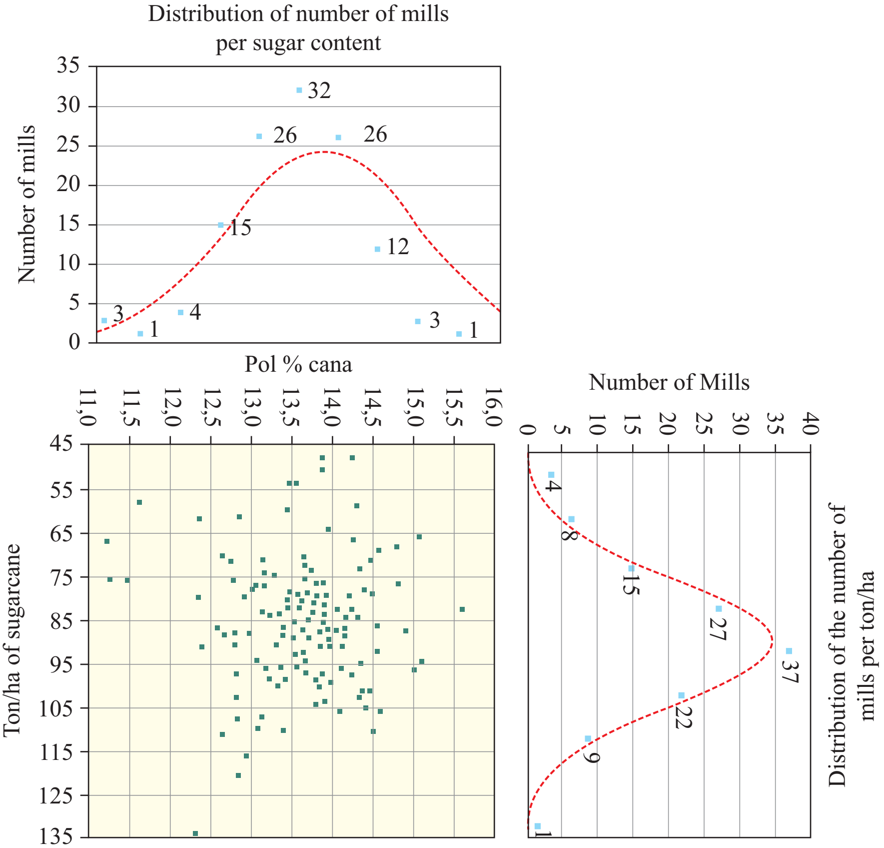

Fig. 18.5 Agricultural productivity distribution in sugarcane mills. (Source: Authors' elaboration based on personal communications)

18.2.3.2 Energy Balance and Production Costs

The choice of crops for ethanol production has a high impact on the energy balance and on the production costs. Energy balance is the ratio of the amount of energy content in the biofuel and the amount of fossil fuel used in the biofuel production (considering direct and indirect fossil fuel consumption).

There is a wide range of crops that can be used for ethanol production besides sugarcane (e.g., corn, sugar beet, manioc/cassava, cereals, and cellulosic materials for 2G ethanol). Figure 18.6 shows a comparison of the energy balance of different raw materials for ethanol production. It illustrates the higher energy balance for sugarcane ethanol (8–10), when compared to the others. In the case of sugarcane, the higher energy balance is due to the use of biomass (only) in the industrial phase as the bagasse is burned in the boilers. For the other crops, energy needs in the

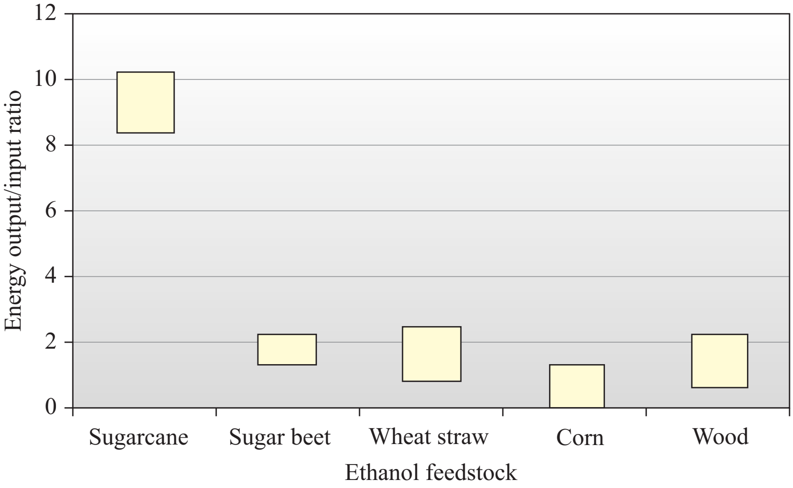

Fig. 18.6 Energy balance (total fossil fuel input vs biofuel produced, on an energy basis) from ethanol production from different feedstocks. Note: Wood ethanol means second-generation ethanol, in a theoretical estimate. (Sources: Authors' elaboration based on Macedo 2005; UK DTI 2003; USDA 1995)

process are supplied by fossil fuels, making the fossil fuel consumption much higher[12] and reducing the global energy balance. This is one of the reasons that results in lower ethanol production costs from sugarcane.

Recent figures confirm the above comparison. For Vietnam, ethanol from cassava has an energy balance equal to 1.61 (Quang-Ha 2017). In Argentina, UNSAM (2015) relates that sugarcane mills using only bagasse (renewable energy) in the boilers could have an energy balance in the range of 7–8, but sugarcane mills using natural gas have a lower energy balance (energy balance is equal to 3.4). In Uruguay, sugarcane ethanol has an energy balance equal to 7.0 (Hernandéz et al. 2017). On the other hand, USDA (Gallagher 2016) reports recent figures for corn ethanol in the United States in a range of 2.15–4.03, higher than those shown in Fig. 18.6 but still lower than sugarcane ethanol. Figure 18.7 shows ranges of production costs, which clearly vary depending on the country and the geographical conditions. In Colombia, for example, sugarcane (anhydrous) ethanol production costs (from molasses) are higher. The said costs in 2014 were equal to US\$ 0.4161 L^{-1}, or US\$ 1.575 $gallon^{-1}$ (GBEP 2014a).

When biofuel mandates are defined, this aims to allow the introduction of a more expensive fuel in the market due to its benefits to the country. However, this policy is introduced with the expectation of decrease in biofuel production costs as the

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[12] In all cases, there is diesel oil consumption in agricultural phase, including sugarcane. However, in the case of sugarcane, there is the possibility of using biogas from vinasse to produce biomethane and to replace diesel in these equipment, making the energy balance of sugarcane ethanol still higher.

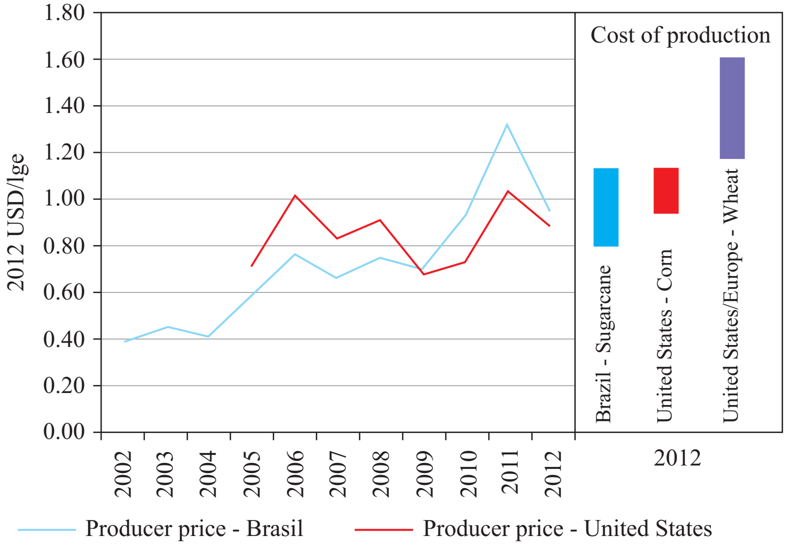

Fig. 18.7 Ethanol production costs from different crops. (Source: IRENA 2013)

volume produced increase (termed as "leaning curves"). Several countries worldwide have mandates but only a few have in fact introduced biofuels. Some examples are:

- Argentina – E-12 (2017)
- Brazil – E-27 (2017)
- Colombia – E-10 (2017)
- Paraguay – E-25 (2017); 27% (2018)

In most cases, the mandates refer to the blend of anhydrous ethanol to gasoline. Brazil seems to be the only country where E-100 (hydrous ethanol) is produced and sold in pump stations (dedicated pump for hydrous ethanol), being used in the so-called flex fuels.

Considering the economic competitiveness of ethanol-gasoline, it is interesting to consider the experience of ethanol from sugarcane in Brazil. In 1980, the cost of ethanol was US$ 0.7 per liter much higher than gasoline at US$ 0.25 per liter. The increase in production lowered these costs dramatically: for each doubling of accumulated production, production cost fills approximately 20%. In year 2000, ethanol production reached a cost of US$ 0.30 per liter, approximately the same for gasoline at Rotterdam price. For 2015, São Paulo mills had a production cost of 0.45–0.46 US$ L^{-1} of hydrous ethanol lower than 2000 prices updated for this year (0.60 US$/L).[13]

Recent updates evaluated the average sugarcane ethanol costs in Brazil, showing its competitiveness with gasoline, as illustrated in Fig. 18.8. For ethanol, pre-tax

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[13] Authors' elaboration based on PECEGE/ESALQ/USP, 2015 (Personal communication).

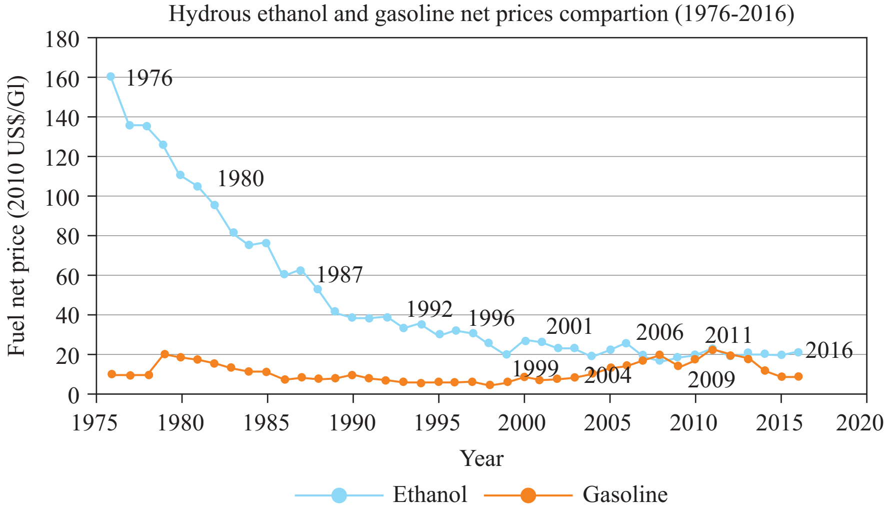

Fig. 18.8 Hydrous (sugarcane) ethanol and gasoline (net) price comparison (1976–2016). (Source: J Goldemberg, P Guardabassi (IEE/USP), 2017, personal communication)

prices were used, which refer to trades in the spot market between producers and distributers, no freight included, for ethanol to be collected at the processing plant (CEPEA 2017). For gasoline, international prices in Rotterdam were used.

18.2.3.3 Sugarcane Ethanol Logistics

The production of biofuels requires the existence or development of a support structure to collect the biomass, transport it to the industrial plant to be processed at, and distribute the biofuel. This is an important issue when several countries are interested in producing sugarcane ethanol. In many countries, like in Sudan, most biofuels are exported – the country exports 90% of its sugarcane ethanol possibly due to the lack of infrastructure and adequate logistics for local distribution, among other factors (Ahmed 2014).

In addition to the above requirements, there is also a need for appropriate facilities for storage. The logistical structure of biofuels is complex and involves local, regional, and long-distance transportation, delivering the product to other consumer centers or even to export (Ahmed 2014; Goldemberg et al. 2017). Depending on market destination of ethanol, the logistics must be handled separately. If the final destination is the internal market, the production must be delivered to a fuel distribution base because of legal reasons; however, if the production is going to be exported, the commercialization can be developed directly from production plant or fuel distribution base (São Paulo Research Foundation [FAPESP] 2008). Regarding the storage facilities, the storage might be done either by the producer storing the production surplus in tanks inside the industry or by the retailer in the terminals to guarantee the supply in the short term (CENBIO 2006).

Infrastructure and logistics are a significant difficulty in African countries. As discussed in IRENA (2016), the lack of roads, water, fertilizer, agriculture extension services, technology development, distribution networks, and market access corresponds to a huge challenge for biofuel (and other goods) production in such countries. However, when the infrastructure is developed for biofuel projects, for sure other agricultural products are positively affected. Therefore, "this can result in a win-win for both biofuels and agriculture, which will ultimately attract more investments in rural areas." The study recommends that a "local and national biofuel market, rather than an export market, can offer much greater economic incentives, which can solve infrastructure problems in the short term."

In Latin America, both in Argentina and Colombia, ethanol is transported in trucks (UNSAM 2015; GBEP 2014a). Brazil has a logistic structure consolidated and quite well distributed for hydrated ethanol or anhydrous ethanol to be blended with gasoline, where both types of ethanol are transported via road, rail, and pipelines (German Technical Cooperation 2005). More recently, an ethanol pipeline is being built in the State of São Paulo, and the first part is already in use from Paulínia to Ribeirão Preto (UNICA 2011), as shown in Fig. 18.9. In the long term, the infrastructure of storage capacity does not seem to be a limiting factor. In Brazil, in 2016, there were 38,500 retailers spread around the country with a storage capacity of 17 million cubic meters. Logistics plays an important role in final prices to consumers; in the case of Brazil, ethanol prices in the Northeast region are quite high due to transportation costs from S-C until NE, and not competitive with gasoline prices.

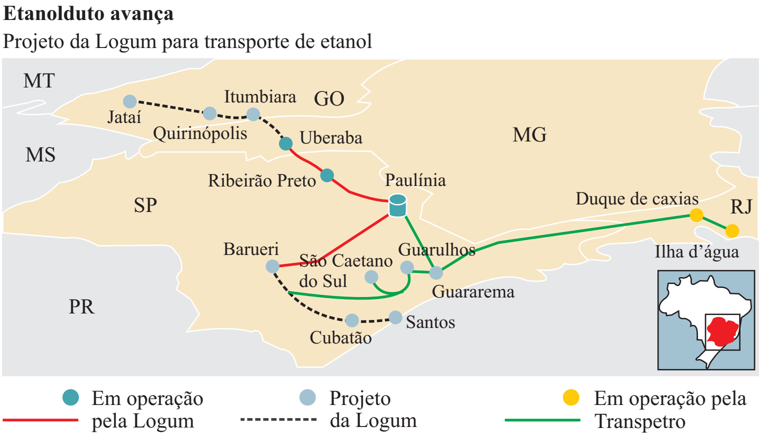

Fig. 18.9 Ethanol transportation through dedicated pipeline in Brazil. (Source: Souza, Z. 2018 (UNICA apud ABAG), personal communication)

As discussed by IRENA (2016) and Nastari (2016), the lack of local infrastructure in developing countries is a bottleneck, not only for sugarcane production and transportation but also for ethanol storage and transportation both for local and international markets.

18.2.3.4 Financial Mechanisms to Incentivize Biofuels

Policies regarding tax differences, when comparing biofuels and fossil fuels, are an interesting mechanism to incentivize biofuels as discussed in REN21 (2017); the same happened in industrialized countries and in Brazil. The Brazilian experience started in the 1970s with the introduction of *ProAlcool* Program, and nowadays it is expanding in different developing countries.

In South Africa, for example, the government, in an effort for poverty alleviation and aiming to increase jobs in rural areas, recognized the need to subsidize the biofuel industry under the Biofuels Industrial Strategy. With a mandated state support included, the government decided a 100% exemption from fuel taxes in the case of bioethanol production (Kohler 2016).

As discussed in Goldemberg et al. (2017), in Brazil, by the end of the 1990s, the federal government removed ethanol subsidies, and, since then, there is no price control from the government. Nowadays, the only incentives in place are allocated in the acquisition of new vehicles on IPI (federal tax for industrialized products) and in Tax on the Circulation of Goods and Services (ICMS). Among the states, the lowest ICMS is in the State of São Paulo (12%), and highest is in the State of Para (30%) with an average of 24% for the country. Flex-fuel vehicles or vehicles powered by ethanol have IPI lower than gasoline vehicles.

Actually, in Brazil, a higher IPI levy on vehicles powered with fuels that have higher emissions of pollutants is a way of internalizing the costs of externalities caused by them. PIS and COFINS taxes are concerned with social security, PIS being the acronym for Program for Social Integration contribution and COFINS the acronym for Contribution for the Financing of Social Security. COFINS is an additional contribution to finance social security based on the gross turnover of the company. The structure of ethanol tax burden can be described as follows (ÚNICA 2007): (i) at industry level, on anhydrous and hydrated ethanol, the PIS/COFINS levy is 3.65% on the revenue after the ethanol sales; (ii) for retailers, the so-called PIS/COFINS levy is 8.2% in the revenue from sales of hydrated ethanol. In the case of anhydrous ethanol, this fuel is blended with gasoline, thus the levy evenly to gasoline. In terms of state tax, the ICMS is a state tax on industry and retailer, and for ethanol, it ranges from 12% to 30%.

These are important mechanisms to make ethanol economically competitive with gasoline for the local consumers, since in Brazil (hydrated) ethanol is sold in every pump station in the country, to be used in flex vehicles. The flex vehicles can run with any blend of ethanol-gasoline, including pure ethanol (E-100). In other countries, where there is only anhydrous ethanol, which is blended with gasoline, price systems can be different. Gasoline prices and taxes can contribute to allow the economic feasibility of (anhydrous) ethanol. A similar policy is used in Brazil for the blend of biodiesel in diesel oil; Petrobras (Brazilian State Oil Company) buys biodiesel from the producers by a price higher than diesel, and the final price of the blend diesel-biodiesel (currently B-8) is sold at a higher price to cover all costs. This policy could be used in other countries starting a biofuel program to allow biofuel economic feasibility.

In fact, in several developing countries, the main difficulties to starting ethanol production are related to:

- The lack of information on the real production costs (to allow the definition of the subsidies when needed) since there are no feasibility studies
- The lack of adequate policies

Mozambique, South Africa, and India are examples of countries facing such difficulties, and the Brazilian experience could be an interesting example to be adopted for such locations.

18.2.3.5 Gross Value Added: Ethanol Sector

There are a few studies regarding the gross value added (GVA) of biofuels (GBEP 2011) compared to the countries' GDP. The most recent figures available are for Colombia and Brazil. For Colombia, GBEP (2014a) showed that it corresponds to 0.54% of Colombian GDP. Regarding Brazil, the sugar/alcohol sector had a GDP share of 2% in 2014 (Neves and Trombin 2014).

Such figures illustrate the importance of the sugarcane ethanol sector, showing how ethanol production can play an important role in producer countries.

18.2.3.6 New Policy Experiences

RENOVABIO[14] is the latest policy introduced in Brazil to incentivize biofuels. It is a cap and trade compensation system where industries consuming and/or distributing fossil fuels must buy carbon credits in the market to keep their carbon emissions in a limit to be specified. These carbon credits will be sold by those sectors using or producing bioenergy. RENOVABIO's main objective is to allow the bioenergy sector to prosper in Brazil, aiming to achieve Brazilian commitments adopted in the context of the Paris Agreement (NDC – National Determined Contribution). RENOVABIO has been approved by the Brazilian Congress in November 2017 and then signed by the President.

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[14] Further details in http://www.mme.gov.br/web/guest/secretarias/petroleo-gas-natural-e-combustiveis-renovaveis/programas/renovabio/principal.

18.3 Conclusion

Despite being a debatable subject, current experiences – mainly the one from Brazil – show that sugarcane ethanol can be produced in sustainable way, in all aspects including environmental, social, and economic. Brazil, for instance, has adopted efficient technologies and improved public policies to guarantee the sustainable ethanol production. Sustainability aspects involve environmental, social, and economic impacts, both for agricultural and industrial phases. All impacts for the agricultural phase are the same both for sugar and ethanol production. Considering this, countries producing only sugar from sugarcane (like India) or both sugar and ethanol (like Brazil) will have to avoid the same impacts in the agricultural phase. On the other hand, the industrial phase of ethanol production is a country-specific issue since it depends on the route of ethanol production being exploited (whether from cane juice or from molasses). The cane ethanol sustainability discussion is happening in other countries as well. Colombia, Argentina, India, and some African countries are investing to produce sugarcane ethanol. In many countries, sugarcane ethanol is not produced from sugarcane juice but from molasses, in order to avoid the food-fuel controversy; however all the sustainability aspects related to sugarcane production are the same. In the case of African countries, there are significant advantages of sustainable large-scale ethanol engenderment, e.g., sugarcane yields per unit area are higher in large-scale plantations, and it has been seen that large-scale plantations contribute to the upgrade of roads, schools, hospitals, and other infrastructure. Moreover, the demand for agricultural inputs such as fertilizers, machines, and services increases, which reduces the vulnerability of small farmers and improves food security. Smallholders can be integrated into the feedstock supply chain for national/regional or international markets, enhancing rural economies. Moreover, bagasse cogeneration can help diversifying energy supply and improving access to energy in rural areas. Sugar mills have great potential for generating surplus electricity to the grid or in some cases to nearby industries or rural households, as happening in Kenya and Uganda through the Cogen for Africa GEF project. In addition, the supply of continuous electricity from biomass can complement the intermittent or seasonal supply of hydropower or other renewables. Also, when used as a cooking fuel to replace charcoal and wood use in urban and rural areas, sugarcane ethanol can be an attractive market. However, its viability will depend on its competitiveness with other ethanol markets and rival fuels.

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Annex: GBEP Sustainability Indicators (GBEP 2011)

Pillars GBEP's work on sustainability indicators was developed under the following three pillars, noting interlinkages between them:		
Environmental	**Social**	**Economic**
Themes GBEP considers the following themes relevant and these guided the development of indicators under these pillars:		
Greenhouse gas emissions; productive capacity of the land and ecosystems; air quality; water availability; use efficiency and quality; biological diversity; land-use change, including indirect effects	Price and supply of a national food basket; access to land, water, and other natural resources; labor conditions; rural and social development; access to energy, human health, and safety	Resource availability and use efficiencies in bioenergy production, conversion, distribution, and end use; economic development; economic viability and competitiveness of bioenergy; access to technology and technological capabilities; energy security/diversification of sources and supply; energy security/infrastructure and logistics for distribution and use
Indicators		
1. Lifecycle GHG emissions	9. Allocation and tenure of land for new bioenergy production	17. Productivity
2. Soil quality	10. Price and supply of a national food basket	18. Net energy balance
3. Harvest levels of wood resources	11. Change in income	19. Gross value added
4. Emissions of non-GHG air pollutants, including air toxics	12. Jobs in the bioenergy sector	20. Change in consumption of fossil fuels and traditional use of biomass
5. Water use and efficiency	13. Change in unpaid time spent by women and children collecting biomass	21. Training and requalification of the workforce
6. Water quality	14. Bioenergy used to expand access tomodern energy services	22. Energy diversity
7. Biological diversity in the landscape	15. Change in mortality and burden of disease attributable to indoor smoke	23. Infrastructure and logistics for distribution of bioenergy
8. Land use and land-use change related to bioenergy feedstock production	16. Incidence of occupational injury, illness, and fatalities	24. Capacity and flexibility of use of bioenergy

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Chapter 19
Future Perspectives of Sugarcane Biofuels

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19.1 Introductory Aspects

Although biofuels are used since the ancient times, they are evaluated today using the technical criteria. These new criteria can be summarized in a few important aspects: low GHG emissions, low cost, no competition with food production, no deforestation, and positive social impacts such as job creation. If these five items are properly addressed, it is possible to consider biofuel production and use to be sustainable.

As far as GHG emissions are concerned, sugarcane ethanol produced in Central-South Brazil is the leading mitigating biofuel with a capacity to reduce around 60% when compared with gasoline (Cortez 2012; Cortez et al. 2016). However, corn ethanol produced in the United States has a relatively smaller mitigating capacity. The second aspect is that biofuels need to be produced at a reasonable low cost to compete with fossil fuels. Biofuel production costs heavily depend on agricultural costs. For sugarcane ethanol, the raw material corresponds to about 70% of overall costs (Braunbeck 2010). Therefore, to make biofuels competitive, one needs to have low agricultural costs, meaning good farming and good practices. In addition, it is important to seek full utilization of the important coproducts.

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In the case of sugarcane ethanol, the industry typically[1] uses the remaining fiber, bagasse, and straw to generate electricity, despite the innumerous developments to produce commercial 2G ethanol. In the case of corn ethanol in the United States, the industry developed a clever way to value its protein-rich residues, integrating it with the beef industry, as we will discuss below. Still in the corn ethanol industry, a new advanced idea is being introduced – the "1.5G ethanol" which increases around 10% ethanol yield, by converting the corn kernel fiber into ethanol (Biorefineries Blog 2017).

The third aspect, avoiding competition with food production, gained attention after several countries started to utilize grains such as corn[2] to produce fuel ethanol (Rosillo-Calle and Johnson 2010; Souza et al. 2015). Many people did not realize that the higher prices of agricultural commodities followed more closely the price of oil than the demand for biofuel production. This was verified after the subprime crisis (2008–2009) when oil and agricultural commodity prices reduced, despite the increasing production of biofuels both in the United States and Brazil, the most important biofuel-producing countries. Also, it is important to remember that in many sugarcane ethanol-producing countries, sugar became a coproduct helping the entire industry economics.

The fourth aspect, related to deforestation process, mainly in Brazil, received attention since the scientific community tried to establish a relationship between biofuel production and deforestation. Deforestation is a phenomenon that is occurring in Brazil since the beginning of its colonization by the Portuguese in the 1500s and intensified since the 1530s when the land occupation process occurred in Brazil. Cattle were used as extensively as possible, sometimes with densities below 0.5 animal units ha^{-1} considering land occupation. Today around 160–200 million hectares are devoted to pastureland and around five million hectares to sugarcane ethanol,[3] meaning there is no possible correlation between both.

The last aspect, related to job creation, can be considered critical, especially in developing countries. The positive social impacts summarized by the job creation figures related to biofuels, especially when compared to fossil fuel production, were studied in more detail for Mozambique (Cunha et al. 2018). It is true that most of the jobs are created in the sugarcane agricultural activities such as the manual harvesting. Although there is a sustainable biofuel production in the world today, not all biofuels can be considered sustainable.[4] Modern agriculture and conversion systems and valorization of biofuels' coproducts are seen as mandatory to render biofuels sustainable. More about aspects of sustainability of sugarcane ethanol produced in Brazil can be found in Cortez (2010) and Cortez (2012).

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[1] In Colombia, part of the sugarcane bagasse is used for pulp and paper.

[2] There was an initial concern that this practice would cause a reduction in corn supply with substantial increases on food production costs.

[3] The total sugarcane planted area in Brazil is nearly 9–10 million hectares, nearly half going to sugar and the other half to ethanol production.

[4] Few developed countries use heavily subsidized agriculture commodities to produce biofuels. Many developing countries produce traditional biomass, by simply extracting it from the environment and using it as bioenergy (Cortez et al. 2018).

19.2 What Makes Sugarcane an Important Bioenergy Crop

Maybe there is no better energy crop than sugarcane. It is a C4 plant, with high energy efficiency presenting excellent opportunities for sugar, ethanol, and other biofuel production. Moreover, it also offers possibilities of bioelectricity and solid fuels such as bagasse, pellets, and briquettes. Additionally, it produces extraordinarily high biomass per unit area and has well-established agricultural practices and milling industry in various countries of the world. In this reference, however, it is important to consider two aspects. The first one is how important it is to use a highly energy-efficient crop to save land and the least abundant resources. Second is that heat, an important component in cold countries, represents an important market for sugarcane coproducts.

19.3 Can Sugarcane Biofuels Still Play a Role to Meet the World Energy Needs and Mitigate GHG Emissions?

There are two questions for sugarcane biofuels concerning their future: what will be their contribution toward meeting the world energy needs and toward mitigating GHG emissions. Related to the energy demand question, it is clear that biofuels cannot alone supply significant parts of future clean energy, but they can give an important contribution. There is not too much available land for biofuels unless important pasture intensification takes place in the world. Roughly, there is about 1.4 billion hectares in agriculture and 3.3 billion hectares in all kinds of pastureland in the world today, as per reports of the Food and Agriculture Organization (FAO 2011). Although there is still abundant land in Africa and Latin America, some other factors such as lack of adequate infrastructure, political stability, and biodiversity protection of ecological sanctuaries represent major restrictions to the expansion of the agricultural frontier. Therefore, more effort will have to be made in achieving higher yields and making less fertile land more productive for sugarcane.

Clean mobility is coming fast, particularly in China, for instance, bringing more alternatives such as solar and wind energy. One of the main markets being addressed naturally is the light and heavy vehicle sector where a significant portion of energy is utilized. The aviation and maritime transportation are excluded because there exist important technical difficulties to adopt electric propulsion in these sectors (Cortez 2014). According to the International Energy Agency (IEA 2017), the introduction of electric vehicles in light transportation, substituting Otto cycle fuels, will be fast in the coming years.[5]

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[5] Fulton (2013) and Fulton et al. (2015) estimated future biofuel volumes demanded, and Leite et al. (2018) discussed the transition from ICEs to electric engines, considering the impacts on biofuel market.

According to IEA (2017), during the transition to electric engines, a significant portion of internal combustion engines (ICEs) will still be running.[6] The phaseout of ICEs is more likely to be slower in developing countries where the population will not have enough financial conditions to afford buying more expensive electric cars. ICEs will probably represent around 40% of vehicles by 2060, and ethanol will have a significant share of Otto cycle fuels (Fulton 2013). Sugarcane ethanol, because of its high GHG mitigating potential, expressed in "gCO_2 $liter^{-1}$," is certainly a good candidate to occupy a key position in this market. However, other aspects of technology are also important such as the engine performance (liter km^{-1}) because the final analysis will compare the efficiency of electric vehicles in terms of GHG emitted to run a certain distance, expressed in terms of "gCO_2 km^{-1}."

19.4 The Evolution of Biofuel Production Systems

Most of the countries, including modern economies, relied on traditional biomass as a source of energy before fossil fuels, and other forms of energy such as hydro were used. By the half of the twentieth century, only underdeveloped countries were still making extensive use of traditional biomass. Biofuels, understood here as a modern type of bioenergy, started to be produced and used in parallel with petroleum, but its more systematic production only took place in the final quarter of the last century.

Brazil was the first country to make a massive use of modern liquid biofuel – bioethanol produced from sugarcane. Conditions were very favorable for Brazil because, in one hand, it was a traditional sugarcane producer and, on the other hand, it experimented a severe energy crisis after the first oil shock in the 1970s.[7] With a well-planned program named *ProAlcool*, the Brazilian Federal Government implemented, with local entrepreneurs and the cooperation of automakers, an ambitious gasoline substitution program. Today, nearly 40% of the total Otto cycle fuel is supplied by sugarcane ethanol, a coproduct of sugar from sugarcane (Cortez et al. 2016).

At the beginning of the *ProAlcool*, several other feedstocks were considered for fuel ethanol production, cassava and sorghum being the most important ones. Also, production scale was an important concern. The original idea was to promote small distilleries, with capacity of up to 20,000 l per day, to benefit small farmers and communities. However, this did not prove to be feasible. On the contrary, the original standard distilleries of 120,000 l per day were much less productive and were bought by larger ones. Today size runs between 500,000 and nearly five to eight

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[6] Electric cars yet have their own limitations like high battery prices. Heavy vehicles are also expected to be slower in adopting this option and therefore may use biofuels for more years or even decades.

[7] The Brazilian Federal Government always understood sugarcane ethanol as an important fuel to be supported for the reasons that range from enhancing national energy security to protecting sugar producers.

million liters per day, a factor of 10–15 between the smallest and the largest ones. This fundamentally occurred because of economies of scale both in the agricultural and industrial sides. However, larger distilleries than eight million liters per day are not economic due to the long transport distances to supply sugarcane to the mill (Cortez et al. 2016).

It can also be stated that not only the large-scale ethanol production did not compete with food production in Brazil but helped to modernize agriculture and its engineering practices. For instance, the recycling of sugarcane ethanol residues such as stillage, fully used as fertilizer, is a common practice in Brazil (Cortez 2010).

However, the so-called Brazilian model[8] of simultaneous production of sugar and ethanol faced recent market-derived difficulties. After the subprime crisis in 2008, new investments declined, and cane productivity dropped associated with climatic conditions and lack of good practices. For these and other reasons, the Brazilian production model needs to be revisited. The world sugar market became highly sensitive, and Brazil may lose its leadership if local producing conditions are not improved and a new model to expand its ethanol production is not created. The new model needs to answer urgent issues, such as land use, and issues related to the domestic market such as the price volatility and logistics of ethanol distribution.

In the United States, the construction of the ethanol production chain went differently. The large-scale ethanol production only started during the 2000s. The US Government then realized fuel ethanol could be a better way to help farmers than practicing set-aside policy, meaning that part of the corn production could be converted to fuel ethanol. Being aware of the difficulties associated with corn as feedstock, the United States created a well-conceived model based on utilizing and valuing all corn ethanol by-products, DDG[9] being the most important one, either on the wet or dry processes.

Today, producing more than 50 billion liters of corn ethanol per year, and being the first world producer, the United States utilizes enormous quantities of DDG to feed animals, mainly beef. The United States uses around 150 million tons of corn year^{-1} (less than a third of its annual corn harvest) to produce almost double of Brazilian sugarcane ethanol and practically the same quantity of beef as Brazil, all that is done using around 15 million ha of corn in the United States.

Today, several corn ethanol projects have been built in Latin America, mostly in Brazil and Argentina. In Brazil, most of these projects are in the states of Mato Grosso and Goiás, considering flex or in integrated operations with sugarcane. This industry is expanding fast, and it is expected to play an important role in Brazilian ethanol supply as a complement of sugarcane as feedstock, particularly in remote areas, knowing that there are, for example, logistics problems to move corn and ethanol to and from Central-South Brazilian region.

Therefore, the analysis concerning production models needs to take into consideration several aspects including market, economics, integration of other industries,

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[8] More aspects of the Brazilian model to produce sugarcane ethanol are given in Cruz et al. (2014).

[9] DDG stands for dry distillers grains. It is the coproduct from corn ethanol and is rich in fiber and protein.

etc. More about sugarcane production models were studied for Africa and Colombia, including issues such as scale and electricity production, and are presented in Cortez et al. (2018).

19.5 The Role of 2G Ethanol as a Prospective Alternative

Biomass is typically composed of relatively smaller portions of sugars, starch, oil, and protein, comparatively to larger portions of fiber. If bioenergy is to become a success and give significant contributions to reduce GHG emissions, more important use of fiber as energy is needed. The more efficient energy use of biomass fiber will certainly have a significant impact on GHG emissions and land use for ethanol production. In the sugarcane case, fiber typically corresponds to 2/3 and sugar to 1/3 of the total dry weight. This results in a fiber/sugar ratio of 2:1. In the so-called energy cane, this ratio can be 3:1, although no significant large plantations have yet demonstrated the feasibility of energy cane (Matsuoka et al. 2014).

Typically, the sugarcane mills use fiber to generate electricity and heat in low-efficient Rankine cycle systems, practically incinerating the bagasse, in most cases. Many times, this occurs due to the lack of competitiveness of bioelectricity since high-pressure boilers and turbines as well as the connection to a nearby electricity grid are relatively expensive. Countries like Mauritius significantly depend on sugarcane bioelectricity, covering 35% of the national demand (Zafar 2018). Lessons from Mauritius are being adopted in Brazil and India, increasing bioelectricity production from sugarcane.

Another important potential refers to the utilization of stillage for the production of biogas. Several attempts were made until the moment to convert and stabilize high BOD stillage from sugarcane ethanol distillation, including its use in trucks at the mills. Although new efforts have recently been made in several countries, the main obstacle is represented by the relatively low price payed to diesel.

Other forms of bioenergy conversion are less efficient and competitive to date. With 2G ethanol occurs, more or less the same difficulty, despite the more significant efforts that have been made. 2G ethanol can be produced either in stand-alone units that use only lignocellulosic material to produce ethanol or in 1G2G plants, where 2G ethanol is integrated in a 1G plant. The major bottlenecks of the 2G ethanol technology are the deconstruction of the lignocellulosic material in the so-called pretreatment operation, the hydrolysis of the cellulosic and hemicellulosic polymers, and the conversion of the pentose sugars to ethanol (Bonomi et al. 2016).

However, no significant commercial results have been demonstrated up to now. The 2G ethanol plants around the world are still struggling to operate. Globally, the important cellulosic ethanol projects are Poet-DSM (Emmetsburg, Iowa, USA), Beta Renewables (Crescentino, Italy), Abengoa (Hugoton, Kansas, USA), Dupont Danisco (Itasca, Illinois, USA), Raízen (Piracicaba, São Paulo, Brazil), and GranBio (São Miguel dos Campos, Alagoas, Brazil). The plants in Brazil use sugarcane bagasse and straw. It is important to remark that several spinoff companies are dedicated to work to solve the most important 2G bottlenecks: pretreatment, enzymatic cocktail production, and fermentation of pentoses.

In Brazil, the two cellulosic ethanol projects, GranBio and Raízen, were co-financed by the BNDES, the Brazilian National Bank for Economic and Social Development. The reason for this support was a study developed with the participation of BNDES that showed that when the 2G ethanol learning curve will become a reality (expected in 10 years), 2G ethanol from sugarcane will be economically advantageous when compared to 1G ethanol (using only sucrose to produce ethanol and diverting the sugarcane fiber to cogenerate electricity) (Junqueira et al. 2017; Milanez et al. 2015).

Up to now the GranBio project has failed to overcome technical difficulties.[10] At the moment, the Raízen plant is the only one in operation and promises to become economically feasible by 2025,[11] if the existing agricultural and technology barriers are overcome. Historically, Brazil has done a significant research effort to develop 2G ethanol. Several decades ago, the COALBRA[12] project in 1979 tried to use a technology developed by the Russians using acid hydrolysis. A demonstration plant was built but was shut down, although this project's aim was focused on wood conversion to methanol (Cortez and Cruz 2014; Silva 2012).

Another initiative was the CTC/Dedini Project financed by FAPESP to install a cellulosic ethanol production of 5000 l of ethanol per day (Cortez and Cruz 2014; Silva 2013). The difficulties associated with sugarcane bagasse supply, the production of inhibitory compounds for fermentation, and a viable use for the fraction of lignin were the most important technical difficulties encountered (Silva and Chandel 2014). In 2005, the Ministry of Science, Technology and Innovation created the Bioethanol Network, coordinated by Rogério Cerqueira Leite (Cortez and Cruz 2014; Leite 2018). The network involved the participation of several researchers from different Brazilian universities aiming to understand what needed to be done to make 2G ethanol work in Brazil. Later the National Laboratory of Bioethanol Science and Technology (CTBE) was created. One of the CTBE areas was the research in 2G ethanol, and a special pilot plant was conceived to develop projects with industry trying to solve the bottlenecks of 2G ethanol from sugarcane. Other centers in Brazil also conducted a research on 2G ethanol, such as the CENPES from Petrobras, and several universities such as UNICAMP and USP-Lorena in São Paulo, UFRJ in Rio de Janeiro and UFPR in Paraná.

Maybe the right position would be not to expect that 2G ethanol can really contribute substantially until its main technological challenges are overcome. That can take many years, but, again, for countries with limited land availability, this process development path is worth to be taken. To elaborate a national policy for biofuel production, where 1G and 2G ethanol have a fundamental role, it is worthwhile to

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[10] https://novoextra.com.br/outras-edicoes/2017/947/39595/fiasco-tecnologico-interrompe-sonho-de-alagoas-produzir-etanol-2g.

[11] http://agencia.fapesp.br/etanol-de-segunda-geracao-podera-ser-economicamente-viavel-a-partir-de-2025/26272/.

[12] COALBRA – Coke and Alcohol Wood S/A.

construct a simulation platform that allows to evaluate sustainability (economic, environmental, and social) impacts of different biomasses, technological routes, and production chains. A tool with these characteristics, the Virtual Sugarcane Biorefinery, was developed and is being used by CTBE to evaluate biofuel production scenarios in Brazil and abroad (Bonomi et al. 2016).

19.6 Potential Markets for Advanced Sugarcane Biofuels in the Future: Aviation and Maritime

Two other important markets for sugarcane biofuels are the aviation and maritime, with different characteristics from each other, but similar size in terms of GHG emissions, around 3–4% of global emissions (Fulton et al. 2015; IEA 2017). The use of renewable biofuels in substitution to fossil fuel is one of the main initiatives toward the reduction of impacts derived from carbon emissions by airline and maritime operations. According to Dermibas (2017), bioethanol is a petrol additive/substitute, and it is possible that wood, straw, and even household wastes may be economically converted to bioethanol, due to its octane number, broader flammability limits, higher flame speeds, and higher heats of vaporization than gasoline. These properties allow for a higher compression ratio, shorter burn time, and leaner burn engine, which lead to theoretical efficiency advantages over gasoline in an internal combustion engine (ICE). Disadvantages of ethanol include its lower energy density than gasoline, its corrosiveness, low flame luminosity, lower vapor pressure, miscibility with water, and toxicity to ecosystems.

19.6.1 The Aviation Market for Biofuels

The aviation market, understanding it as the jet fuel market, is probably the most complex since the present expected solution is to seek for “drop-in” fuels, meaning a fuel that can comply with strict requirements established by the turbine manufacturers and the certification agency (ASTM 2011, 2012).

The aviation industry has committed itself to cut 50% of GHG emissions by 2050 over 2005 levels[13] and is struggling to develop more efficient planes and procedures. However, there is no other technical solution other than substituting conventional jet fuel by biofuel. Innumerous tests and commercial flights have demonstrated technical feasibility for biofuels produced by different feedstocks and multiple pathways, but none has proven to be economically sustainable. The main difficulty rises in producing sustainable low-cost feedstocks, since it corresponds to more than half of the overall biojet fuel cost (Lu and Christian 2018).

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[13] https://www.iata.org/pressroom/pr/Pages/2009-12-08-01.aspx.

Despite all efforts made by airplane manufacturers and airlines, time will probably play an important role in this process and also the possibility to review the "drop-in" requirement. Road maps were powerful tools to identify the opportunities and bottlenecks of the aviation sector to reduce GHG emissions in several countries.[14] A Brazilian road map was constructed for biofuels for aviation including more than 30 stakeholders. Several pathways were developed considering sugarcane as feedstock, including the cane juice, fiber, and ethanol itself (Cortez 2014). Scientists of the Brazilian Bioethanol Science and Technology Laboratory (CTBE) evaluated the technical, economic, and environmental performances of renewable jet fuel production integrated in Brazilian sugarcane biorefineries among other feedstocks (Klein et al. 2018).

A particularly different investigation was published by Chiong et al. (2018), who reviewed the direct usage of six potential alternative liquid biofuels for gas turbine and their combustion performances. Biofuels without oxygen in their molecules have similar energy density to that of jet fuel and enable application in aviation gas turbine especially at high altitude. Bioethanol was considered to be a possible choice of biofuels for gas turbine despite its significantly low flash point, low viscosity, and high vapor pressure, since its application in gas turbine requires modification in the fuel delivery and fuel storage systems. Studies of bioethanol in gas turbine are relatively scarce although the fuel is widely applied in reciprocating gasoline engine. They show that the robust nature of gas turbine and the development of multi-fuel-capable gas turbine enable operation with biofuels.

Mawhood et al. (2016) studied the most feasible technologies and commercialization for biofuels for aviation and identified the two for sugar-derived biojet fuels: direct sugars to hydrocarbons (DSHC) and the ones from alcohol-to-jet fuel (ATJ). Most processes focus on simple hexose sugars derived from sugarcane, sweet sorghum, and maize, which are easier to ferment. The proprietary Biofene® technology uses sugarcane-derived glucose to produce the isoprenoid farnesene, to replace petroleum products (first commercial plant is located in Brotas, Brazil, and is operating since December 2012, with a capacity to produce up to 50 million liters of farnesene per annum). The other sugar-derived pathway is the alcohol to jet (ATJ) which covers a wide range of technologies producing jet fuel from biomass via alcohol intermediates. The alcohols are converted to hydrocarbon fuel via a process of dehydration, oligomerization, and hydrogenation. However, complete feedstock-to-fuel process chains for ATJ are not commercially operating. The technologies to synthesize alcohol intermediates are better developed than those to convert the intermediates to jet fuel.

The major ethanol producers of the world are the United States and Brazil, the European Union, and China, whereas the main biodiesel producers include the European Union and Indonesia followed by Brazil and the United States. In 2017, Dermibas announced the world goals and hopes for the future's biofuels and highlighted the potential for alternatives for the road, aviation, and maritime fueling, offering potential for reduced carbon footprint. His work predicts the use of liquid

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[14] That is, www.sustainableaviation.co.uk, and www.csiro.au.

biofuels as biojet fuels in the future, despite their higher production costs (biojet fuels are still 2–4 times more expensive than petroleum jet fuels).

19.6.2 The Maritime Transport Sector and Biofuels

The maritime transport sector (MTS) is vital for global economy due to its efficiency for worldwide trade. A large growth of demand for MTS fuels is expected due to the increase of global population. MTS can collaborate to reduce their fuel environmental impact by reducing GHG and particulate material emissions using several strategies including improvements in engine technology, implementation of control strategies, and the use of cleaner burning fuels. MTS today is responsible for 15%, 13%, and 3% of the world emissions of NO_X, SO_X, and CO_2, respectively (International Chamber of Shipping [ICS] 2014; International Maritime Organization [IMO] 2014; United Nations Conference on Trade and Development 2009), and also contributes toward the reduction in health quality of coastal areas (Gysel et al. 2014; Tao et al. 2013; Winebrake et al. 2009). The majority of NO_X and particulate matter emissions of harbor craft vessels operating in inland waterways are released near port communities (Gysel et al. 2014).

Marine fuels are mainly of poor quality with high sulfur content, classified into two categories: lower-cost residual and heavy fuel oils (HFO) (Hsieh et al. 2013). Such fuels are widely used at low-speed vessels, and distilled higher-quality oils or marine gasoil (MGO) is extensively consumed by medium- and high-speed vessels and in auxiliary engines of low-speed vessels (International Agency and Agência Nacional do Petróleo Gás Natural e Biocombustíveis [ANP] 2010; McGill et al. 2013).

MARPOL, the international regulation of maritime sector, defines global limit emissions for NO_x of 14.4 g/kWh for low-speed vessels and SO_x limits of 0.5%m/m until 2020. In restricted areas, called ECAs (Emission Control Areas) and SECAs (Sulfur Emission Control Areas), the NO_x and SO_x emission limits are 3.4 g/kWh and 0.10%m/m, respectively, for low-speed vessels (Lack et al. 2011; MARPOL 2010, Wang et al. 2007).

Righi et al. (2011) analyzed the full replacement of heavy fuel oil for maritime fleet and found that biofuels can theoretically meet the fuel demand of the global fleet, provided that the shipping share of total fuel consumption does not increase. They suggested that biofuels could be effectively mixed with low-sulfur fossil fuel, according to the local availability of each component. As positive examples, South and Central America and Africa were found to have the largest potential for biofuel production, due to their potential increase of arable land. They modeled that ships moving from these regions might adopt blends with a high biofuel fraction. On the other hand, the biofuel fraction can be lowered and replaced with low-sulfur marine gas oil, where the availability of biofuels is lower. Given these possible future limitations, the results of this work should therefore be regarded as an upper limit estimate and may represent a useful reference for future studies addressing the impact of biofuels in more detailed traffic scenarios.

In 2012, the US Department of Energy (DOE)'s Bioenergy Technologies Office initiated a research program to evaluate the compatibility of fast pyrolysis bio-oil with infrastructure materials. The International Maritime Organization (2014) presented their overview of non-petroleum test and qualification program indicating the intention not to replace aviation (F-44) nor ship propulsion fuel (F-76) but to approve non-petroleum-based sources per process to produce them. No oxygenated biofuels requiring changes to their platforms nor to their distribution practices were targeted (Andrew et al. 2012). Biofuel was also suggested as potential solution to lower emissions and reduce net carbon emissions without requiring significant changes to the current infrastructure (Gysel et al. 2014).

According to Taljegard et al. (2014), the future of marine fuels and propulsion technologies needs to minimize the total costs associated with CO_2 reductions globally. However, their industry and users are not expected to choose the lowest cost solution, but political will, energy security issues, country-specific interests, and practical obstacles are factors that are expected to influence future fuels. They estimated the difference in cost for ships running on different fuels depending on the cost of engines and fuel tanks and other extra costs such as gas alarm systems, pipelines, or fuel processors. By using model and simulation tools, it was found that the cost for the diesel engine would be between 500 and 700 USD kW^{-1} depending on the size of the ships, and when running on fossil methanol and biofuels, there is a slightly higher engine cost per kW due to extra cost for fuel processing.

A quite elegant approach to plan the future of biofuels for maritime and for aviation sectors takes into account the contribution and importance of the specific needs for transport of each industrial/agrotechnology sector (Korhonen et al. 2014). Marine shipping is very important for the pulp and paper industry (PPI) and has studied transport options. The development of sustainable transportation strategies contributes toward long-term competitiveness of the PPI, especially if new strategic innovation-oriented partnerships are developed to use transportation biofuels.

As the industrial production of renewable biofuels to replace a fraction of conventional fossil marine fuels require substantial amounts of feedstocks, Galindo et al. (2018) have selected fast pyrolysis bio-oil of energy sugarcane (FPECane) to prepare homogenous blends to be used as biofuels. Its complex mixture of hundreds of compounds is easily transported, as the bulk biomass volume is substantially reduced to a liquid biofuel. Technical and economic feasibility of the FPECane mixed with sugarcane bioethanol and marine diesel were investigated. Extensive and broad reviews have lately described properties of fast pyrolysis bio-oils, including the petroleomic characterization and model-based formulation of biofuel blends (Stas et al. 2014) and material compatibility (Qu et al. 2013).

Nicodème et al. (2018) discussed the competition of two ways to produce bioenergy from sugarcane, the biochemical conversion and the cogeneration processes, and the advantages and disadvantages of each pathway. The liquid bioethanol sector is currently facing an increasing demand for anhydrous ethanol especially due to the policy adopted in several countries worldwide to raise the proportion of bioethanol mixed in gasoline.

A few other authors have studied biofuels for MTS; their blends with butanol and marine fuels have been appointed by Chong and Bridgwater (2016) as short- to medium-term solution to mitigate emissions from the MTS. Very recently, Li et al. (2018) studied the stability of ternary systems of pyrolytic lignin and a series of mixed solvents. Ternary phase diagrams were powerful to predict phase separation of bio-oil systems mostly for transport, storage, and industrial operations.

19.7 Future Improvements in Cane Biofuel Production

Although sugarcane ethanol has been demonstrated to be economically competitive with gasoline, it still needs cost reduction to expand in a highly competitive future. For the other cane biofuels, used in aviation or maritime, the challenges are even more important, but possible to be addressed. When cost reduction is analyzed, immediately it can be seen that feedstock plays a key role in the process since it represents around 70% of the overall biofuel cost. Feedstock availability and low cost are essential factors, together with sustainability aspects, such as low emissions in its life cycle. It is evident that cane biofuels will become more economical and cost-effective as a result of undergoing R&D efforts and technological improvements.

Therefore, all efforts should be devoted to keep sugarcane production costs as low as possible while observing other sustainability aspects. To summarize the main points which will lead to an increase in sugarcane biofuel adoption and those deserving research and development in this regard, a short list of role players and actions considered to be essential to promote competitive sustainable sugarcane biofuels is presented as follows:

1. Climate change mitigation efforts – The role of sugarcane biofuels in the world energy matrix will increase as the world's efforts against climate change are enhanced.
2. Government policies – Government policies in cane-producing countries will be the major decisive factor. Policy matters are expected to be more in favor of biofuels with the passage of time.
3. Potential available locations – After Brazil, African countries, Thailand, and Colombia can especially be potential locations producing more cane biofuels. In such countries, there is land availability, and the production is expected to rise in the future.
4. Role of crop improvement – Crop improvement will definitely be a major factor. Enhancement in cane resilience, biomass, and sucrose contents, as well as resistance against biotic factors, will lead to more cane production reducing its production costs and enhancing its yields in the same available land.
5. Success of energy cane – Success and adoption of energy cane will also help in producing huge biomass on limited land or on land which can otherwise not be utilized for crop production as this type of cane has huge biotic and abiotic stress tolerance.

6. Developments in fermentation – Better fermentation technology, and enzyme production in the crop itself, will also help. Better microbial strains will be available.
7. 2G ethanol production – 2G ethanol production improvements are expected in the future and will play a huge role once this technology is matured and cost-effective.

A final comment about the list presented above: the first two items are a recognition that policy certainly plays a key role in implementing and maintaining biofuels alive in a competitive fuel economy. Items 3, 4, and 5 address important issues related to land and feedstock, considering critical factors in any biofuel production. And finally, the last two items observe that process engineering is still an important aspect, if not mandatory, to comply with the strict requirements of this new industry.

19.8 Conclusion

Concerning the aviation and maritime sectors, more effort is needed both in legislation and incentives, such as tax reduction and creation of market for biofuels. Technological barriers are still the major obstacles to produce low-cost cane biofuels, although the potential for future use is considered very positive. Also, the drop-in aviation requirement is a major barrier; therefore airplane turbine manufacturers need to conduct the necessary work to revise or reconsider it. Both sectors offer excellent opportunities and have not yet received the necessary attention. Being responsible for substantial emissions, the maritime opportunity is to develop biofuels with low emissions of NO_X, SO_X, and $CO_{2.}$ The most important difficulty remains the development of a lower-cost converting technology. Existing fast pyrolysis technologies need still to have their cost reduced. As far as 2G ethanol is concern, more engineering is probably needed to overcome pretreatment problems, pointed to be the most important issue. Many countries, including the United States, Brazil, and those from Europe, have devoted significant efforts and financial resources, but it seems that economic feasibility is still to be demonstrated and reached. Crop improvement will also be playing a crucial role in reducing the feedstock costs. Lastly, it is important to mention that integrated production systems, trying to interconnect energy, food, and fiber while protecting our forests, seem to be the way to the future for sugarcane bioenergy. In the twenty-first century, the world seems to be committed to protect the environment and to phase out fossil fuels, so there is a great opportunity for sugarcane biofuels.

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