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).

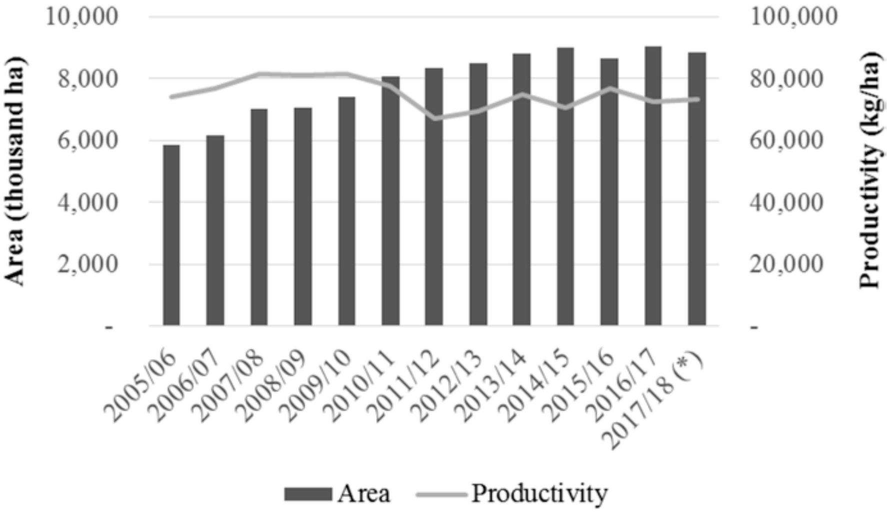

Fig. 5.1 Timeline of planted area and productivity from sugarcane crop in Brazil. (Source: CONAB 2017). ∗Values estimated

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).

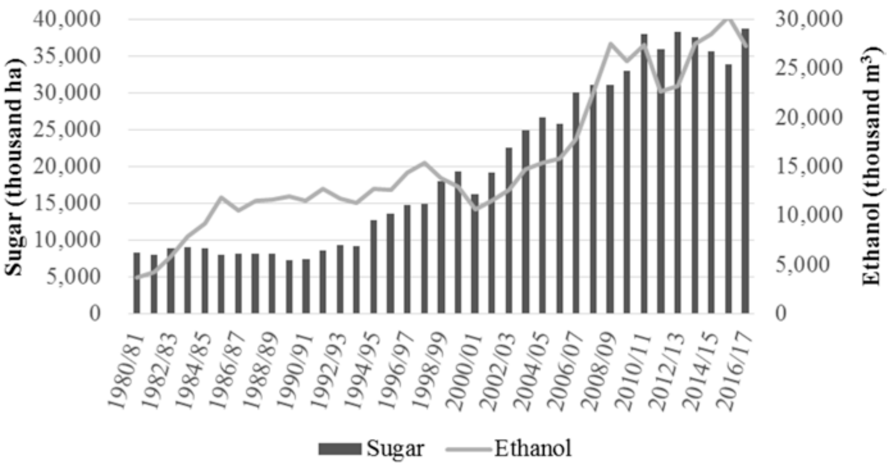

Fig. 5.2 Evolution of sugar and ethanol production in Brazil. (Source: UNICA 2017)

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 Abastecimento (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)

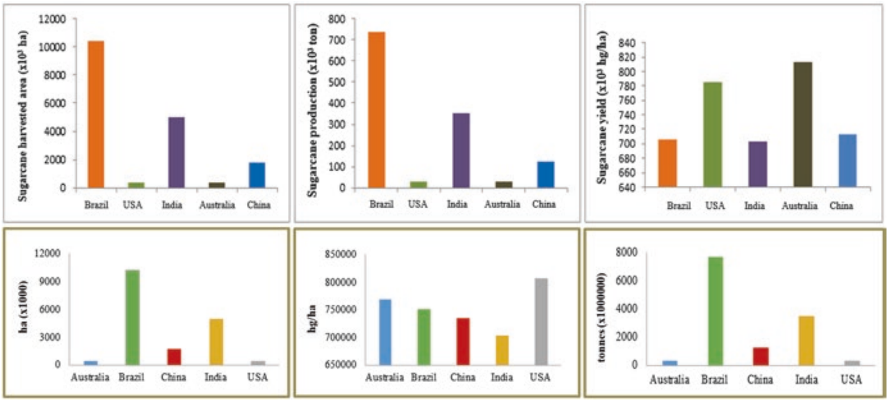

Fig. 5.4 Sugarcane area (ha), production (ton), and yield (hg ha^{-1}) for the major global producers in 2016. (Source: FAO 2016)

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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