Chapter 11
Sugarcane Biofuel Production in Colombia

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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

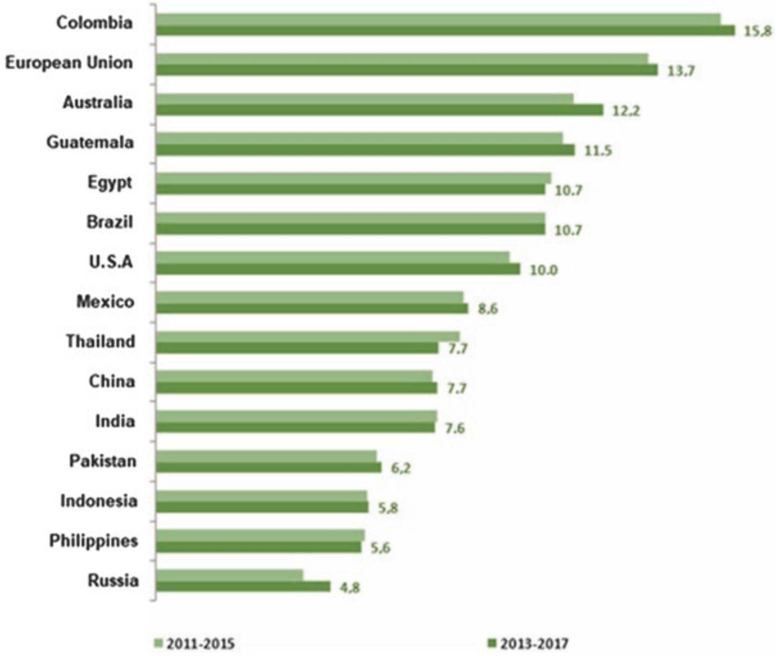

Fig. 11.1 Global sugar productivity indicator—main producing countries (tons of sugar per hectare). (Source: ASOCAÑA 2017)

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).

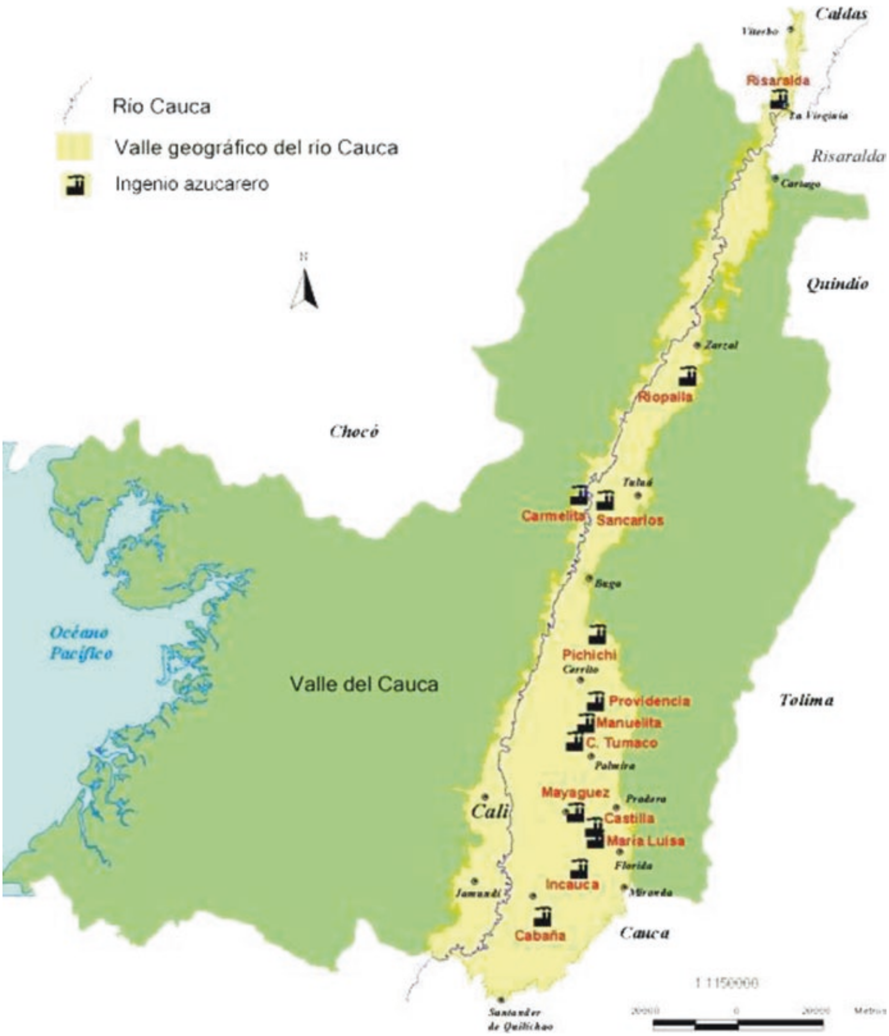

Fig. 11.2 Valley of the Cauca River region and locations of its sugarcane mills. (Source: Cenicaña 2017b)

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.

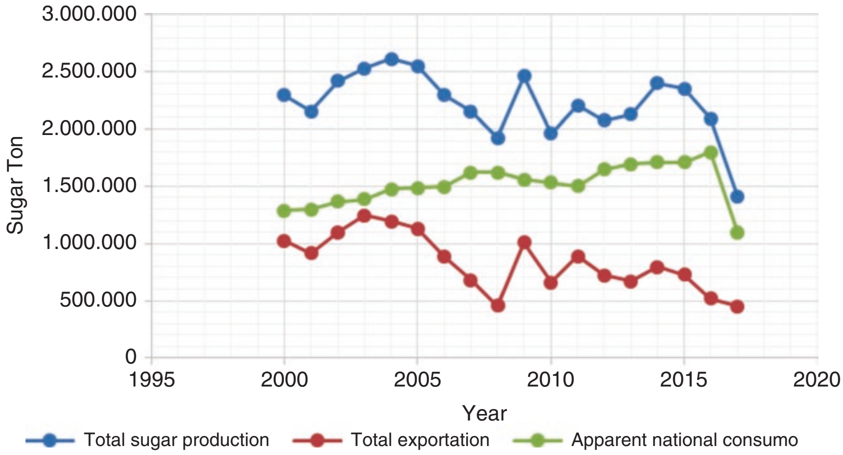

Fig. 11.3 Production, consumption, and export of sugar in Colombia *The data for 2017 are preliminary, subject to changes by the FEPA audit (Sugar Price Stabilization Fund). (Source: ASOCAÑA 2016a)

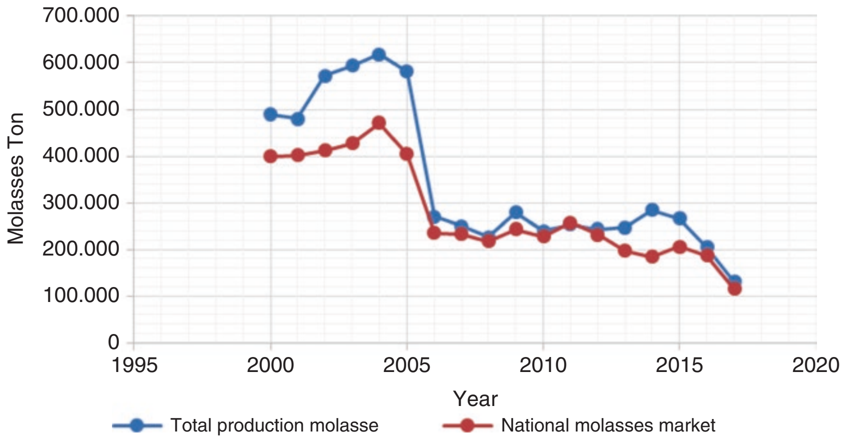

Fig. 11.4 Production and national market in Colombia *The data for 2017 are preliminary, subject to changes by the FEPA audit (Sugar Price Stabilization Fund). Source: ASOCAÑA 2016a)

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.

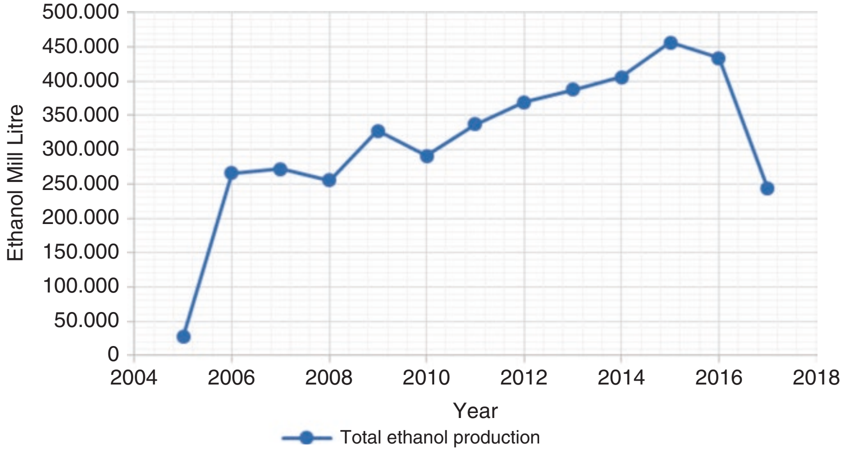

Fig. 11.5 Ethanol production in Colombia ∗The data for 2017 are preliminary, subject to changes by the FEPA audit (Sugar Price Stabilization Fund). (Source: ASOCAÑA 2016a)

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.

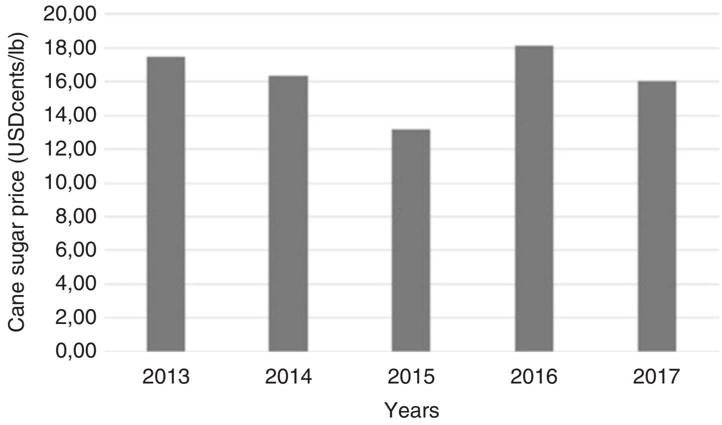

Fig. 11.6 Evolution of the international cane sugar price over last 4 years. (Source: ASOCAÑA 2016a)

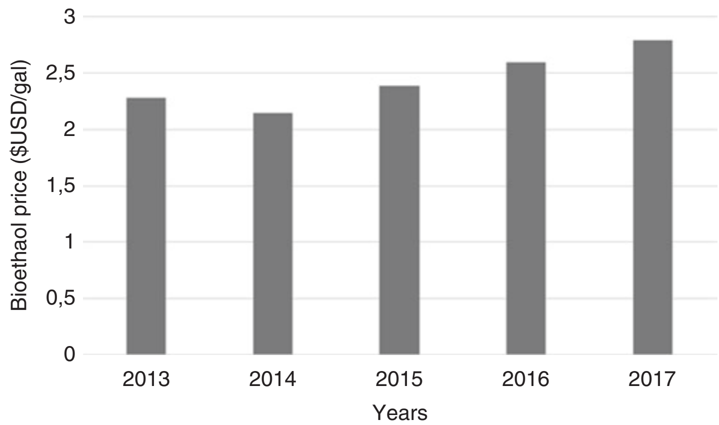

Fig. 11.7 Evolution of bioethanol price over last 4 years in Colombia. (Source: FedeBiocombustibles 2016)

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).

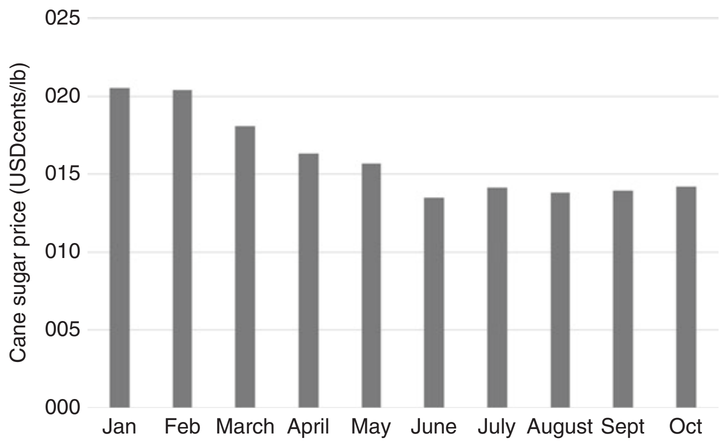

Fig. 11.8 Cane sugar price during the year 2016 in Colombia. (Source: ASOCAÑA 2016a)

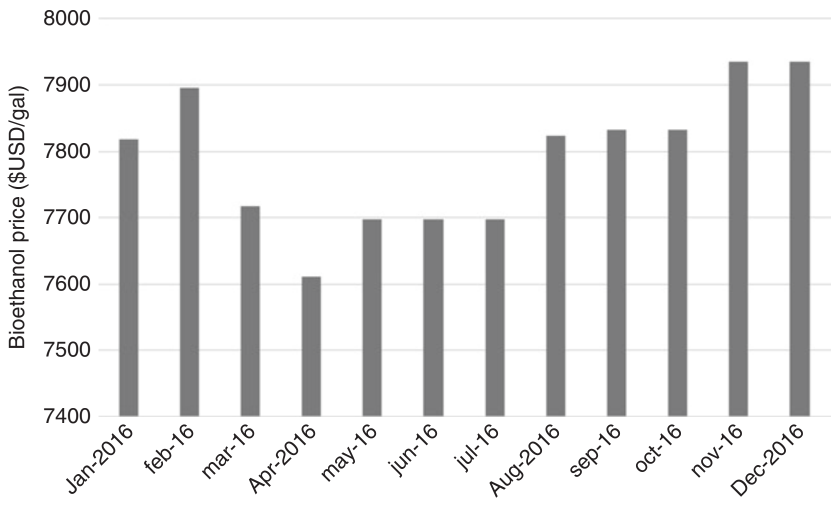

Fig. 11.9 Ethanol price during the year 2016 in Colombia. (Source: FedeBiocombustibles 2016)

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%

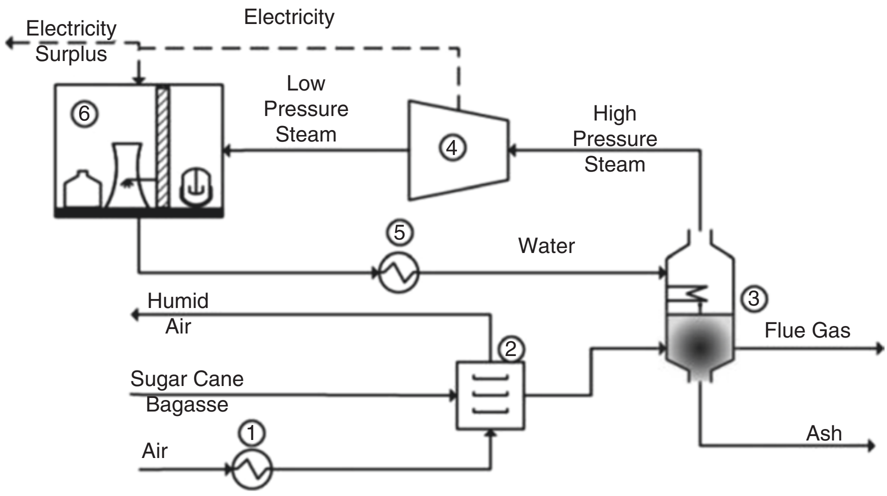

Fig. 11.10 Biomass steam turbine cogeneration system. (1) Heater; (2) dryer; (3) furnace; (4) steam turbine; (5) water condenser; (6) chemical process. (Source: Reprinted by permission from Springer Nature: Springer Nature, Rincón et al. (2014)), Copyright © 2013, Springer Nature (2013))

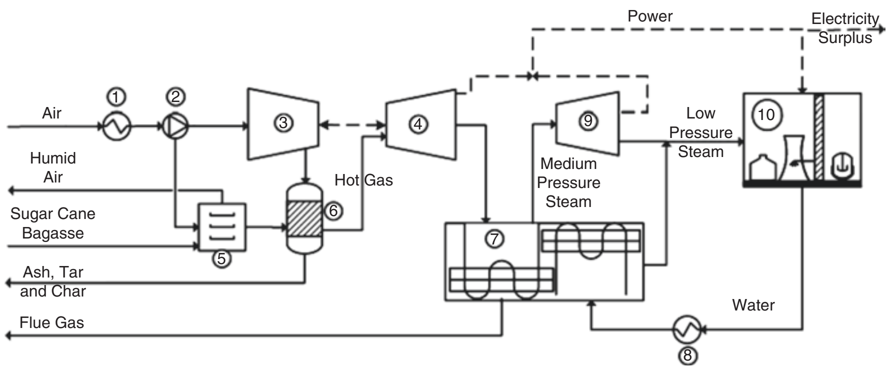

Fig. 11.11 Biomass-integrated gasification-combined cycle cogeneration system. (1) Heater; (2) divisor; (3) compressor; (4) primary gas turbine; (5) dryer; (6) integrated gasification and combustion system; (7) heat recovery steam generator; (8) water condenser; (9) secondary steam turbine; (10) chemical 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).

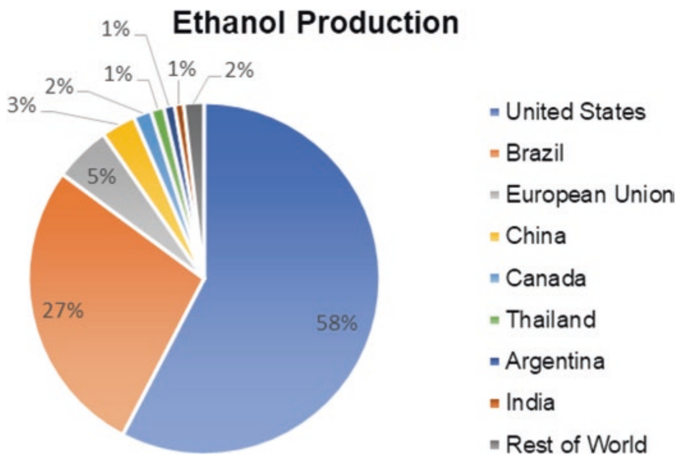

Fig. 11.12 Production of ethanol in the world. (Source: RFA 2017)

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

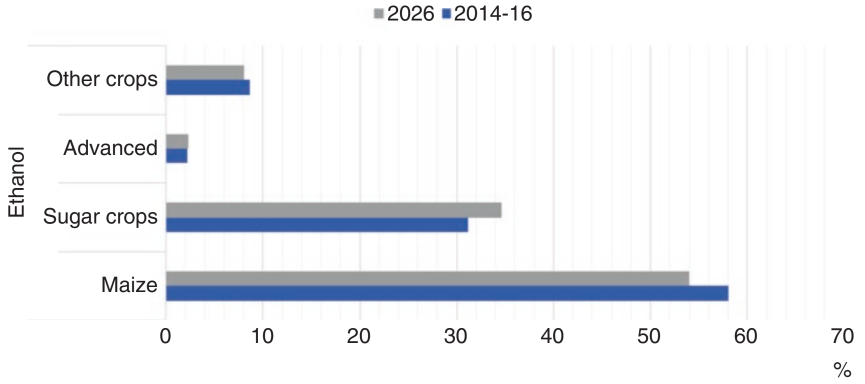

Fig. 11.13 Sources of ethanol production in the world. (Source: OECD/FAO 2017)

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

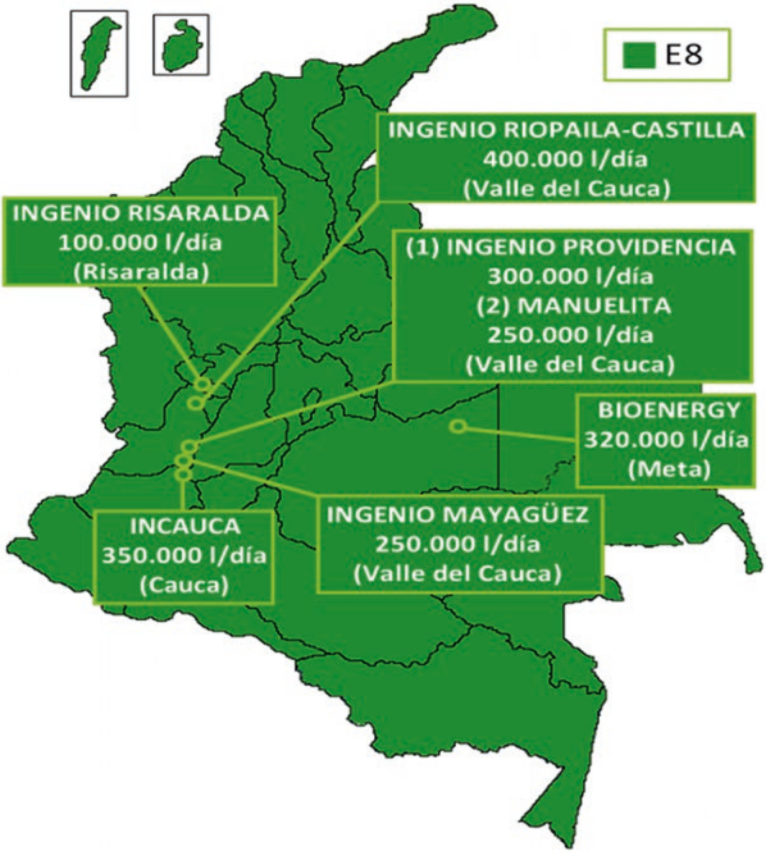

Fig. 11.14 Distribution of ethanol facilities in Colombia. (Source: FedeBiocombustibles 2017b)

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

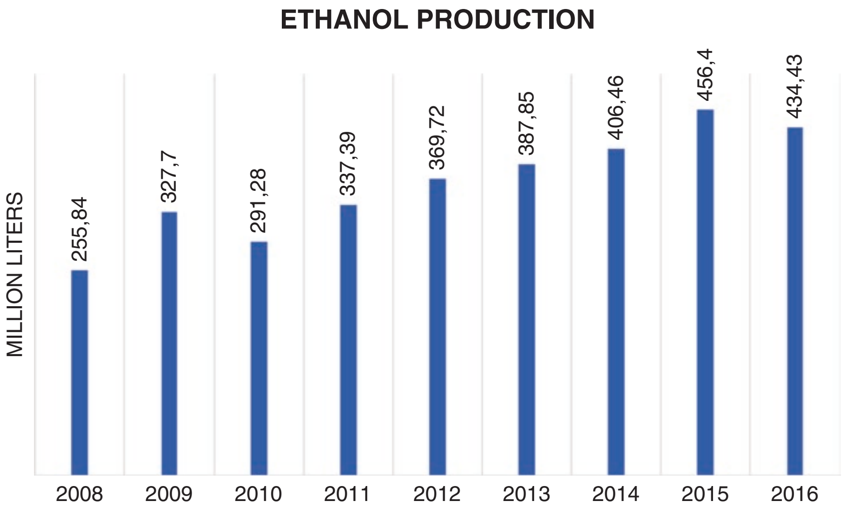

Fig. 11.15 Sugarcane ethanol production in Colombia. (Source: FedeBiocombustibles 2017b)

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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References

Alam F, Date A, Rasjidin R, Mobin S, Moria H, Baqui A (2012) Biofuel from Algae- Is it a viable alternative? Procedia Eng 49:221–227. https://doi.org/10.1016/j.proeng.2012.10.131

Amaral BS, Ventura LMB, Amaral AS, Francisco Neto RA, Gioda A (2017) Concentration profiles of regulated and unregulated pollutants emitted from the combustion of soybean biodiesel and diesel/biodiesel blend originating of a diesel cycle engine. J Braz Chem Soc 28:659–668

Arbeláez MA, Estacio A, Olivera M (2010) Impacto socioeconómico del sector azucarero colombiano en la economía nacional y regional. Cuadernos de Fedesarrollo 31:100

ASOCAÑA (2015) Informe anual 2015–2016. Sector Agroindustrial de la Caña. http://www.asocana.org/modules/documentos/3/348.aspx. Accessed 12 Jan 2018

ASOCAÑA (2016a) Balance azucarero colombiano Asocaña 2000–2017 (Toneladas). Sector Agroindustrial de la Caña. http://www.asocana.org/modules/documentos/5528.aspx. Accessed 11 Jan 2017

ASOCAÑA (2016b) El Sector Azucarero Colombiano En La Actualidad. Sector Agroindustrial de La Caña. http://www.asocana.org/publico/info.aspx?Cid=215. Accessed 11 Jan 2018

ASOCAÑA (2017) Informe anual de Asocaña con aspectos generales del Sector Azucarero Colombiano 2016–2017 y Anexos estadísticos. Sector Agroindustrial de la Caña. http://www.asocana.org/modules/documentos/14140.aspx. Accessed 30 Nov 2017

ASOCAÑA (2018) Anexo estadístico – Informe anual 2016–2017 Sector Agroindustrial de la Caña. http://www.asocana.org/modules/documentos/14144.aspx. Accessed 20 Apr 2018

Bailis R, Solomon BD, Moser C, Hildebrandt T (2014) Biofuel sustainability in Latin America and the Caribbean – a review of recent experiences and future prospects. Biofuels 5(5):469–485. https://doi.org/10.1080/17597269.2014.992001

Balza LH, Espinasa R, Serebrisky T (2016) Luces encendidas?: Necesidades de energía para América Latina y el Caribe al 2040. Banco Interamerciano de Desarrollo. https://publications.iadb.org/handle/11319/7361?locale-attribute=es&. Accessed 11 Jan 2018

Bezerra TL, Ragauskas AJ (2016) A review of sugarcane bagasse for second-generation bioethanol and biopower production. Biofuels Bioprod Biorefin 10(5):634–647. https://doi.org/10.1002/bbb.1662

BNDES & CGEE (2008) Sugarcane-based bioethanol : energy for sustainable development. Banco Nacional de Desenvolvimento Econômico e Social http://sugarcane.org/resource-library/studies/BNDES. Accessed 11 Jan 2018

Bracmort K (2015) The Renewable Fuel Standard (RFS): cellulosic biofuels. Congressional Research Service. https://www.lankford.senate.gov/imo/media/doc/The%20Renewable%20Fuel%20Standard%20Cellulosic%20Biofuels.pdf. Accessed 30 Nov 2017

Cardona CA, Quintero JA, Paz IC (2010) Production of bioethanol from sugarcane bagasse: status and perspectives. Bioresour Technol 101(13):4754–4766. https://doi.org/10.1016/j.biortech.2009.10.097

Cenicaña (2017a) Centro de Investigación de la Caña de Azúcar de Colombia. http://www.cenicana.org/web/. Accessed 30 Nov 2017

Cenicaña (2017b) Mapa Región Azucarera. Centro de Investigación de la Caña de Azúcar de Colombia. http://www.cenicana.org/pictures/quienes_somos/map_region_azucarera.jpg. Accessed 30 Nov 2017

Chen JCP, Chou CC (1993) Cane sugar handbook: a manual for cane sugar manufacturers and their chemists, 12th edn. Wiley, New York/Chichester/Brisbane/Toronto/Singapore

Choi S, Song CW, Shin JH, Lee SY (2015) Biorefineries for the production of top building block chemicals and their derivatives. Metab Eng 28(Supplement C):223–239. https://doi.org/10.1016/j.ymben.2014.12.007

Colombo G, Ocampo-Duque W, Rinaldi F (2014) Challenges in bioenergy production from sugarcane mills in developing countries: a case study. Energies 7:5874–5898. https://doi.org/10.3390/en7095874

Cordovés Herrera M (1999) Cane, sugar and the environment. Paper presented at the Cuba/FAO International Sugar Conference, 7–9 December, Cuba

Cortés-Marín EA, Ciro-Velázquez HJ (2011) Biofuels and energy self-sufficiency: Colombian experience. In: Mads B (ed) Biofuel's engineering process technology. IntechOpen, London. https://doi.org/10.5772/17199

Cremonez PA, Feroldi M, Feiden A, Gustavo Teleken J, José Gris D, Dieter J, de Rossi E, Antonelli J (2015) Current scenario and prospects of use of liquid biofuels in South America. Renew Sust Energ Rev 43(Supplement C):352–362. https://doi.org/10.1016/j.rser.2014.11.064

Daza Serna LV, Solarte Toro JC, Serna Loaiza S, Chacón Perez Y, Cardona Alzate CA (2016) Agricultural waste management through energy producing biorefineries: the Colombian case. Waste Biomass Valorization 7(4):789–798. https://doi.org/10.1007/s12649-016-9576-3

Delgadillo-Vargas O, Garcia-Ruiz R, Forero-Álvarez J (2016) Fertilising techniques and nutrient balances in the agriculture industrialization transition: the case of sugarcane in the Cauca river valley (Colombia), 1943–2010. Agric Ecosyst Environ 218(Supplement C):150–162. https://doi.org/10.1016/j.agee.2015.11.003

Deshmukh R, Jacobson A, Chamberlin C, Kammen D (2013) Thermal gasification or direct combustion? Comparison of advanced cogeneration systems in the sugarcane industry. Biomass Bioenergy 55(Supplement C):163–174. https://doi.org/10.1016/j.biombioe.2013.01.033

Donaldson GK, Eliot AC, Flint D, Maggio-Hall LA, Nagarajan V (2005) Fermentive production of four carbon alcohols. EUA Patent US7993889B1, 2005-10-26, Wilmington

Dutta K, Daverey A, Lin J-G (2014) Evolution retrospective for alternative fuels: first to fourth generation. Renew Energy 69:114–122. https://doi.org/10.1016/j.renene.2014.02.044

El Bassam N, Maegaard P, Schlichting ML (2013) Biomass and bioenergy. In: El Bassam N, Maegaard P, Schlichting ML (eds) Distributed renewable energies for off-grid communities. Elsevier, Amsterdam, pp 125–165. https://doi.org/10.1016/B978-0-12-397178-4.00009-8

Ezeji TC, Liu S, Qureshi N (2014) Chapter 9 – Mixed sugar fermentation by clostridia and metabolic engineering for butanol production. In: Qureshi N, Hodge D, Vertes A (eds) Biorefineries. Elsevier, Amsterdam, pp 191–204. https://doi.org/10.1016/B978-0-444-59498-3.00009-9
FedeBiocombustibles (2016) Precios de Biodiesel. http://www.fedebiocombustibles.com/estadistica-precios-titulo-Biodiesel.htm. Accessed 12 Jan 2018
FedeBiocombustibles (2017a) Bioetanol: política para la preservación del ambiente. Federación Nacional de Biocombustibles de Colombia. http://www.fedebiocombustibles.com/nota-web-id-2915.htm. Accessed 12 Jan 2018
FedeBiocombustibles (2017b) Información Estadística Sector Biocombustibles. Federación Nacional de Biocombustibles de Colombia. http://www.fedebiocombustibles.com/v3/estadistica-mostrar_info-titulo-Alcohol_Carburante(Etanol).htm. Accessed 29 Nov 2017
Fileni DM (2017) Ethanol programs in developing countries: prospects for ethanol exports UNICA, Brazilian Sugarcane Industry Association http://english.unica.com.br/files/documents/ethanol. Accessed 12 Jan 2018
Fiorese G, Catenacci M, Verdolini E, Bosetti V (2013) Advanced biofuels: future perspectives from an expert elicitation survey. Energy Policy 56. (Supplement C:293–311. https://doi.org/10.1016/j.enpol.2012.12.061
Food and Agriculture Organization (2008) The state of food and agriculture. http://www.fao.org/tempref/docrep/fao/011/i0100e/i0100e.pdf. Accessed 30 Nov 2017
Food and Agriculture Organization (2015) Food and agriculture data. http://www.fao.org/faostat/en/#home. Accessed 30 Nov 2017
Gauch M (2012) Evaluación del ciclo de vida de la cadena de producción de biocombustibles en Colombia. SBC, Sostenibilidad de Biocombustibles en Colombia. https://www.fedebiocombustibles.com/files/EvaluacionDelCicloDeVidaDeLaCadenaDeProduccionDeBiocombustiblesEnColombia-MarcelGauch.pdf. Accessed 07 May 2018
Gilbert AJ, Huerta M (2016) Sugar annual Colombia. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Sugar%20Annual_Bogota_Colombia_4-15-2016.pdf. Accessed 30 Nov 2017
González X (2017) Ingenios producen 270 megavatios hora de cogeneración de energía. La Republica. https://www.larepublica.co/economia/ingenios-producen-270-megavatios-hora-de-cogeneracion-de-energia-2501901. Accessed 07 May 2018
Gonzalez-Salazar MA, Venturini M, Poganietz W-R, Finkenrath M, Leal MRV (2017) Combining an accelerated deployment of bioenergy and land use strategies: review and insights for a post-conflict scenario in Colombia. Renew Sust Energ Rev 73(Suppl C):159–177. https://doi.org/10.1016/j.rser.2017.01.082
Gronewold N (2011) Colombia pursues sweet dream of becoming a sugar-cane ethanol powerhouse. E&E Publishing. http://www.nytimes.com/gwire/2011/05/09/09greenwire-colombia-pursues-sweet-dream-of-becoming-a-sug-91543.html?pagewanted=all. Accessed 30 Nov 2017
Guarieiro LLN, Guerreiro ETA, Amparo KKS, Manera VB, Regis ACD, Santos AG, Ferreira VP, Leão DJ, Torres EA, de Andrade JB (2014) Assessment of the use of oxygenated fuels on emissions and performance of a diesel engine. Microchem J 117(Supplement C):94–99. https://doi.org/10.1016/j.microc.2014.06.004
Gutiérrez LF, Sánchez ÓJ, Cardona CA (2009) Process integration possibilities for biodiesel production from palm oil using ethanol obtained from lignocellulosic residues of oil palm industry. Bioresour Technol 100(3):1227–1237. https://doi.org/10.1016/j.biortech.2008.09.001
Hanney P, Amend E, de Dargent GC, Hoffman E, Joseph S, Secko D, Longstaff H (2012) Advanced biofuels: a public deliberation. an information booklet. Concordia Science Journalism Project, Concordia University, Montreal
Haubensak O, Rutherford TF (2011) Future prospects for renewable energy in Colombia. http://www.files.ethz.ch/cepe/2011TermPapers/p65.pdf. Accessed 12 Jan 2018
Hoang NV, Furtado A, Botha FC, Simmons BA, Henry RJ (2015) Potential for genetic improvement of sugarcane as a source of biomass for biofuels. Front Bioeng Biotechnol 3:182. https://doi.org/10.3389/fbioe.2015.00182

Iakovou E, Karagiannidis A, Vlachos D, Toka A, Malamakis A (2010) Waste biomass-to-energy supply chain management: a critical synthesis. Waste Manag 30(10):1860–1870. https://doi.org/10.1016/j.wasman.2010.02.030

International Service for the Acqusition of Agro-biotech Applications (2007) Carbon capture and storage: the "Fourth Generation" biofuels. SEAsiaCenter. http://www.isaaa.org/kc/cropbiotechupdate/biofuels/default.asp?Date=10/12/2007. Accessed 04 Apr 2018

International Trade Administration (2016) Renewable fuels top markets report. US Departament of Commerce https://www.trade.gov/topmarkets/pdf/Renewable_Fuels_Fuel_Ethanol.pdf. Accessed 06 Apr 2018

Jaramillo Obando JJ, Cardona CA (2011) Análisis de la producción de biobutanol en la fermentación acetobutilica con clostridium saccharoperbutylacetonicum N1–4 ATCC13564. Revista Facultad de Ingeniería Universidad de Antioquia, pp 36–45

Jeihanipour A, Bashiri R (2015) Perspective of biofuels from wastes. In: Karimi K (ed) Lignocellulose-based bioproducts. Springer International Publishing, Cham, pp 37–83. https://doi.org/10.1007/978-3-319-14033-9_2

Kojima M, Mitchell D, Ward W (2007) Considering trade policies for liquid biofuels. Renew Energy. https://www.wilsoncenter.org/sites/default/files/brazil.considering.trade.policiesforbiofuels.pdf. Accessed 06 Apr 2018

Londoño LF (2016) Aspectos generales del sector azucarero colombiano 2015–2016. http://www.asocana.org/modules/documentos/14143.aspx. Accessed 30 Nov 2017

Londoño Capurro LF (2017) Desempeño de la Agroindustria de la Caña en Colombia 2016–2017. Sector Azucarero Colombiano. http://www.asocana.org/modules/documentos/14143.aspx. Accessed 30 Apr 2018

Marin FR (2016) Understanding sugarcane production, biofuels, and market volatility in Brazil—A research perspective. Outlook on Agriculture 45(2):75–77. https://doi.org/10.1177/0030727016649802

MINMINAS (2017) Concepto técnico sobre la situación de abastecimiento de alcohol carburante en el pais para los meses de marzo y abril de 2017. Ministerio de Minas y Energía. https://www.minminas.gov.co/documents/10180/20166813/Concepto+t%C3%A9cnico+alcohol+carburante+-+marzo-abril2017.pdf/dd464146-96d7-4ba0-b051-c03a7b95513c. Accessed 11 Nov 2017

Moncada J, El-Halwagi MM, Cardona CA (2013) Techno-economic analysis for a sugarcane biorefinery: Colombian case. Bioresour Technol 135(Supplement C):533–543. https://doi.org/10.1016/j.biortech.2012.08.137

Montoya D, Spitia S, Silva E, Schwarz WH (2000) Isolation of mesophilic solvent-producing clostridia from Colombian sources: physiological characterization, solvent production and polysaccharide hydrolysis. J Biotechnol 79(2):117–126. https://doi.org/10.1016/S0168-1656(00)00218-2

Moon YH, Han KJ, Kim D, Day DF (2015) Enhanced production of butanol and isopropanol from sugarcane molasses using Clostridium beijerinckii optinoii. Biotechnol Bioprocess Eng 20(5):871–877. https://doi.org/10.1007/s12257-015-0323-6

National Biodiesel Board (2017) Biodiesel technical information. Nat Renew Energy Lab (NREL). http://biodiesel.org/docs/ffs-basics/adm-fact-sheet-biodiesel-technical-information.pdf?sfvrsn=4. Accessed 18 Dec 2017

Organization for Economic Co-operation and Development, Food and Agriculture Organization (2017) Agricultural outlook 2017–2026. https://doi.org/10.1787/agr_outlook-2017-en. Accessed 20 Nov 2017

Organization for Economic Co-operation Development, Food and Agriculture Organization (2017) Agricultural outlook. https://doi.org/10.1787/d9e81f72-en. Accessed 11 Nov 2017

Ottinger RL (2009) Biofuels – potential, problems & solutions. Fordham Environ Law Rev 19(2):253–263

Portafolio (2015) Cogeneración, negocio alterno de los ingenios. Portafolio.co. http://www.portafolio.co/negocios/empresas/cogeneracion-negocio-alterno-ingenios-27096. Accessed 07 May 2018

PROCOLOMBIA (2018) The world invests in Colombia: investments in biofuels sector. Procolombia – exports tourism investment country brand. http://www.investincolombia.com.co/sectors/agribusiness/biofuels.html. Accessed 10 Apr 2018

Quintero JA, Rincón LE, Cardona CA (2011) Production of bioethanol from agroindustrial residues as feedstocks. In: Pandey A, Larroche C, Ricke SC, Dussap C-G, Gnansounou E (eds) Biofuels. Academic Press, Amsterdam, pp 251–285. https://doi.org/10.1016/B978-0-12-385099-7.00011-5

Qureshi N (2014) Integrated bioprocessing and simultaneous product recovery for butanol production. In: Qureshi N, Hodge D, Vertes A (eds) Biorefineries. Elsevier, Amsterdam, pp 205–223. https://doi.org/10.1016/B978-0-444-59498-3.00010-5

Qureshi N, Liu S, Ezeji TC (2013) Cellulosic butanol production from agricultural biomass and residues: recent advances in technology. In: Lee JW (ed) Advanced biofuels and bioproducts. Springer, New York, pp 247–265. https://doi.org/10.1007/978-1-4614-3348-4_15

Ramírez-Velásquez A, Montoya RIA, Montoya RLA (2012) Análisis del modelo Mezcla de Marketing de la industria del bioetanol en Colombia. Acta Agronómica 61:177–191

Rau B, Gomez LA (2017) Biofuels annual report: Colombia. USDA Global Agriculture Information Network (GAIN). https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Bogota_Colombia_9-22-2017.pdf. Accessed 22 Sep 2017

Renewable Fuels Association (2017) World fuel ethanol production. http://www.ethanolrfa.org/resources/industry/statistics/#1454099103927-61e598f7-7643. Accessed 28 Nov 2017

Renewable Fuels Association (2018) Industry Statistics – World fuel ethanol production. http://www.ethanolrfa.org/resources/industry/statistics/#1454098996479-8715d404-e546. Accessed 17 Apr 2018

Rincón LE, Becerra LA, Moncada J, Cardona CA (2014) Techno-economic analysis of the use of fired cogeneration systems based on sugar cane bagasse in South Eastern and Mid-Western regions of Mexico. Waste Biomass Valorization 5(2):189–198. https://doi.org/10.1007/s12649-013-9224-0

Rodado C (2011) Política pública y perspectivas de los biocombustibles y la generación de energía renovable en el actual gobierno. Revista Palmas 32(11):121–126

Romano SD, Sorichetti PA (2011) Introduction to biodiesel production. In: Romano SD, Sorichetti PA (eds) Dielectric spectroscopy in biodiesel production and characterization. Spriner, London, pp 7–27. https://doi.org/10.1007/978-1-84996-519-4_2

Rosillo-Calle F, Walter A (2006) Global market for bioethanol: historical trends and future prospects. Energy Sustain Dev 10(1):20–32. https://doi.org/10.1016/S0973-0826(08)60504-9

Sánchez OJ, Cardona CA (2007) Producción del alcohol carburante: una alternativa para el desarrollo agroindustrial, 1st edn. Universidad Nacional de Colombia, Sede Manizales, Manizales, Caldas

Sánchez ÓJ, Cardona CA (2008) Trends in biotechnological production of fuel ethanol from different feedstocks. Bioresour Technol 99(13):5270–5295. https://doi.org/10.1016/j.biortech.2007.11.013

Scavage (2018) Importaciones de 2905.14.10.00. Scavage Colombia. https://www.scavage.com/trade?menu=co.import&query=product:2905141000&group=2,-1&resolve=1. Accessed 07 May 2018

Sebayang AH, Masjuki HH, Ong HC, Dharma S, Silitonga AS, Mahlia TMI, Aditiya HB (2016) A perspective on bioethanol production from biomass as alternative fuel for spark ignition engine. RSC Adv 6(18):14964–14992. https://doi.org/10.1039/C5RA24983J

STATISTA (2017) Sugar production worldwide 2017/18. The statistics portal. https://www.statista.com/statistics/249679/total-production-of-sugar-worldwide/. Accessed 18 Nov 2017

Tew TL, Cobill RM (2008) Genetic improvement of sugarcane (*Saccharum spp.*) as an energy crop. In: Vermerris W (ed) Genetic improvement of bioenergy crops. Springer, New York, pp 273–294. https://doi.org/10.1007/978-0-387-70805-8_9

The Netherlands Programmes for Sustainable Biomass (2013) Biomass opportunities in Colombia. https://english.rvo.nl/sites/default/files/2013/12/Factsheet%20Biomass%20Opportunities%20Colombia%202013.pdf. Accessed 12 Nov 2017

Toasa J (2009) Colombia: a new ethanol producer on the rise? USDA, United States Department of Agriculture Economic Research Service. https://www.ers.usda.gov/webdocs/publications/40465/10981_wrs0901.pdf?v=41057. Accessed 20 Nov 2017

Unidad de Planeación Minero Energética (2016) Informe Mensual De Variables De Generación Y Del Mercado Eléctrico Colombiano. http://www.siel.gov.co/portals/0/generacion/2016/Segui_variables_dic_2016.pdf. Accessed 11 Nov 2017

United States Department of Agriculture (2017a) Brazil biofuels annual. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_9-15-2017.pdf. Accessed 15 Sep 2017

United States Department of Agriculture (2017b) India biofuels annual. https://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-27-2017.pdf. Accessed 27 Nov 2017

United States Department of Agriculture (2017c) Sugar: world markets and trade. https://apps.fas.usda.gov/psdonline/circulars/Sugar.pdf. Accessed 30 Nov 2017

Vargas G, Lastra LA, Ramírez GD, Solís MA (2017) The diatraea complex (lepidoptera: crambidae) in Colombia's Cauca river valley: making a case for the geographically localized approach. Neotrop Entomol 47(3):395–402. https://doi.org/10.1007/s13744-017-0555-6

Vázquez HJ, Dacosta O (2007) Fermentación alcohólica: Una opción para la producción de energía renovable a partir de desechos agrícolas. Ingeniería, investigación y tecnología 8:249–259

Vega BJP (2017) Colombia tiene la mayor productividad azucarera. La República. https://www.larepublica.co/economia/colombia-tiene-la-mayor-productividad-azucarera-2482881. Accessed 03 Nov 2017

Verheye W (2010) Growth and production of sugarcane. In: Verheye WH, Bayles MB (eds) Soils, plant growth and crop production, vol 2. UNESCO-EOLSS Publishers, Paris

Villamizar ML, Brown CD (2016) Modelling triazines in the valley of the River Cauca, Colombia, using the annualized agricultural non-point source pollution model. Agr Water Manage 177(Supplement C):24–36. https://doi.org/10.1016/j.agwat.2016.06.010

Waclawovsky AJ, Sato PM, Lembke CG, Moore PH, Souza GM (2010) Sugarcane for bioenergy production: an assessment of yield and regulation of sucrose content. Plant Biotechnol J 8(3):263–276. https://doi.org/10.1111/j.1467-7652.2009.00491.x

Wade J (2017) Colombian ethanol producer bioenergy is increasing output toward capacity of 500,000 liters per day. Finance Colombe. http://www.financecolombia.com/colombia-ethanol-bioenergy-sets-output-goal-of-500000-liters-per-day/. Accessed 04 Out 2017

Wang M (2009) Ethanol: the complete energy lifecycle picture. U.S. Department of Energy (DOE) https://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/ethanol_brochure_color.pdf. Accessed 28 Nov 2017

Your Renewable News (2017) Colombia eyes higher ethanol blends in gasoline. http://www.yourrenewablenews.com/colombia+eyes+higher+ethanol+blends+in+gasoline_142224.html. Accessed 10 Apr 2018

Zah R, Gmünder S, Gauch M, Mira D, Toro C, Arango C (2012) Introducción. In: Banco Interamericano de Desarrollo (BID), Ministerio de Minas y Energía (eds) Evaluación del ciclo de vida de la cadena de producción de biocombustibles en Colombia. p 11

Zhang J, Yu L, Lin M, Yan Q, Yang S-T (2017) n-Butanol production from sucrose and sugarcane juice by engineered Clostridium tyrobutyricum overexpressing sucrose catabolism genes and adhE2. Bioresour Technol 233(Suppl C):51–57. https://doi.org/10.1016/j.biortech.2017.02.079