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

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2.1 Introduction

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

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

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

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

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

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

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

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

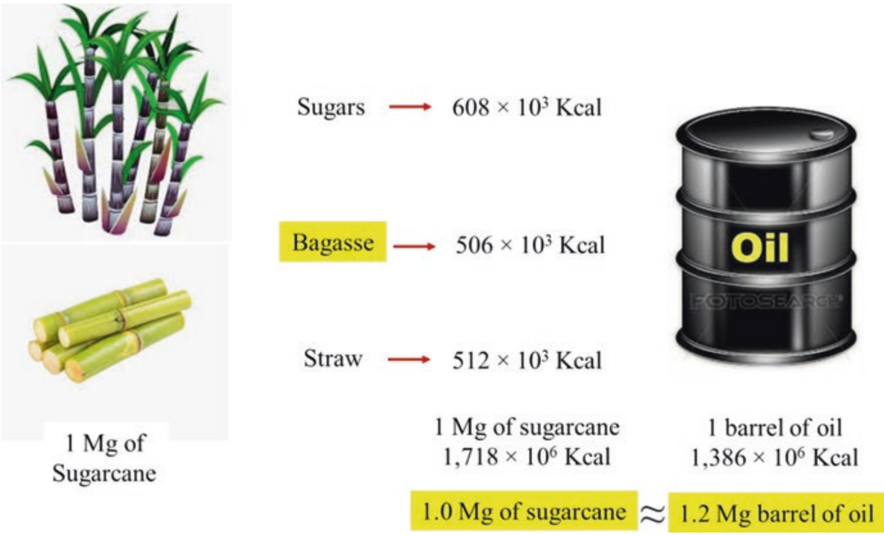

Fig. 2.1 Comparison of energy contents of sugarcane against gasoline. (Adapted from Silva 2009)

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

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

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

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

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

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

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

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

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

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

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

2.2.1 Production Process

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

2.2.1.1 Broth Chemical Treatment

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

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

2.2.1.2 Concentration Step for Sugar and Bioethanol Production

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

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

2.2.1.3 Fermentation

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

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

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

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

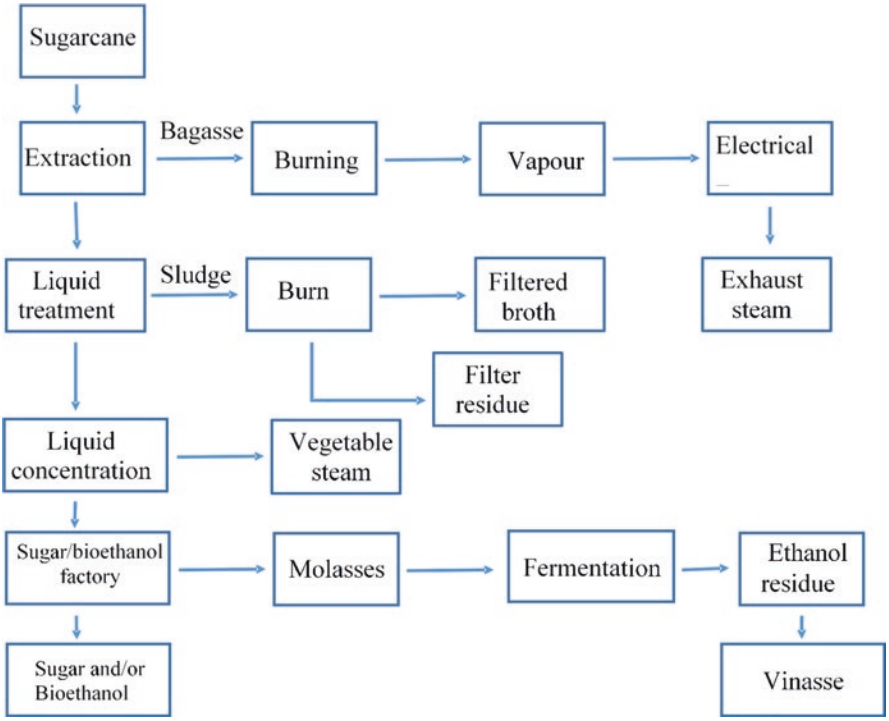

Fig. 2.2 Main steps and processes for bioethanol (first-generation) and sugar production from sugarcane. (Adapted from Silva 2009)

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

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

2.3 Biomass for Cane Biofuels (Second-Generation Bioethanol)

2.3.1 Biomass Composition of Sugarcane

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

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

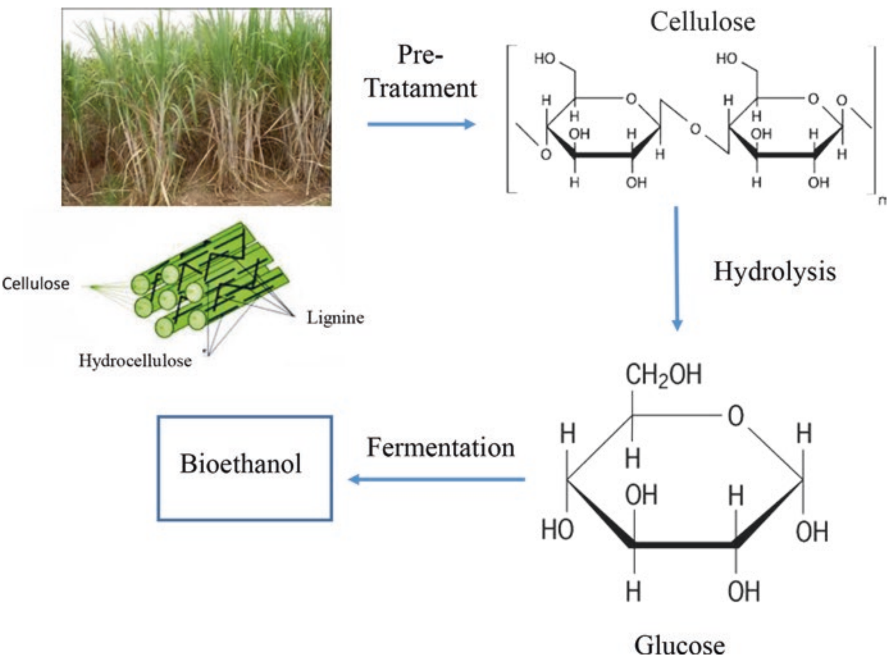

Fig. 2.3 Schematic representation of bioethanol from lignocellulosic biomass (second-generation biofuel). (Adapted from Santos et al. 2012a)

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

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

2.3.2 Sugarcane Biomass for Biofuels

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

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

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

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

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

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

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

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

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

Adapted from Bernardo Neto (2009)

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

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

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

2.3.3 *Employment of Bagasse for Other Means*

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

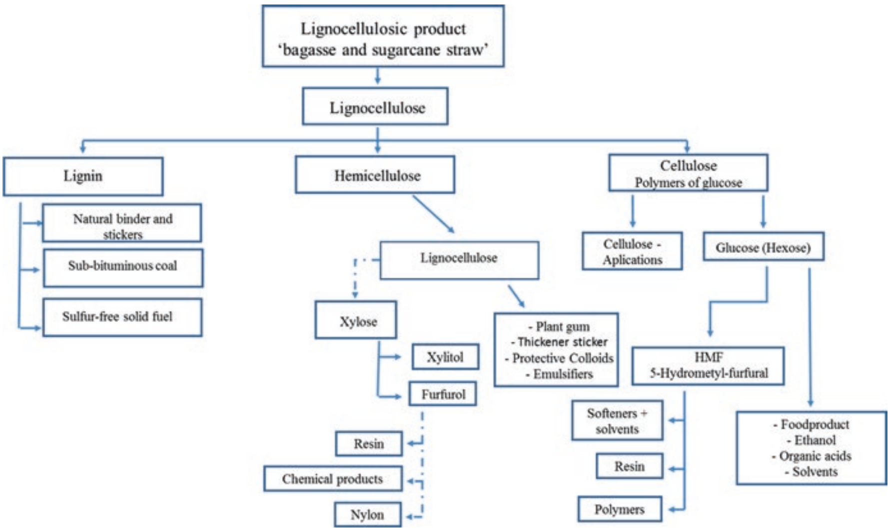

Fig. 2.4 Schematic diagram for bioethanol and other derivatives' production through second-generation process. (Adapted from Bernardo Neto 2009)

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

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

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

2.4 Sugarcane for Bioelectricity Production

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

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

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

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

2.5 Sugarcane Straw for Energy Production

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

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

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

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

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

2.6 Challenges and Constraints

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

2.7 Conclusion

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

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