# A review of sugarcane bagasse for second-generation bioethanol and biopower production

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## Abstract

Sugarcane bagasse is a large-volume agriculture residue that is generated on a ~540 million metric tons per year basis globally[1, 2] with the top three producing countries in Latin America being Brazil (~181 million metric ton yr$^{-1}$),[3] Mexico (~15 million metric ton yr$^{-1}$)[4] and Colombia (~7 million metric ton yr$^{-1}$),[5] respectively.[6] Given sustainability concerns and the need to maximize the utilization of bioresources, the use of sugarcane bagasse is receiving significant attention in biorefining applications, as it is a promising resource for the conversion to biofuels and biopower. This review will provide a comprehensive review of bagasse, its chemical constituents and on-going research into its utilization as a feedstock for cellulosic ethanol and electricity generation.

Keywords: sugarcane bagasse; bioethanol; biopower; second-generation

## 1 Introduction

In the past few decades, the high consumption of fossil fuels has led to an increase use of difficult to recover petroleum reserves, which have heightened environmental concerns along with energy security issues. These issues, in addition to global climate change due to greenhouse gas emissions, have led researchers to explore alternative fuels based on sustainable bioresources. Agro-energy crops and plant residues are two of the most promising low-cost, sustainable biomaterials for biofuel and power generation.

First generation bioethanol has been widely used for vehicle fuels, lowering net carbon dioxide emissions compared to fossil fuels. However, the increasing demand for ethanol requires high feedstock production and an increase in land usage. This could impact biodiversity and competition with food crops, yielding in increases in food prices in addition to limited economic growth. Second generation biofuels could avoid many of these concerns since it relies on nonfood bioresources, such as lignocellulosics. These lignocellulosic materials are relatively inexpensive and available in large quantities. One of the most commonly examined lignocellulosic materials for second-generation ethanol production is sugarcane bagasse.[7-10]

Sugarcane is a versatile plant grown for sugar production, and it’s major by-product is bagasse.[11] Bagasse is the residue obtained after sugarcane is milled for juice extraction. In sugarcane production, the bagasse retrieved from crops is roughly 27-28 dry weight % of plant biomass.[1, 12] It is a highly heterogeneous material that consists roughly of 20-30% lignin, and 40-45% cellulose and 30-35% hemicellulose[13] with limited amounts of extractives and ash. Its composition makes it a promising feedstock for second-generation biofuel production. Similar to other lignocellulosic materials, sugarcane bagasse has low nutritional value, which precludes concerns about the food vs. fuel debate. A variety of species of sugarcane, *Saccharum spp*, are grown in Latin America, which leads it to numerous differing resources of bagasse, which is generally underutilized. Furthermore, bagasse represents approximately 0.3 metric ton for every 1 metric ton of sugarcane[1] grown and is often considered a waste stream. A comprehensive understanding of bagasse chemical constituents and its physical and chemical characteristic changes associated with the bioconversion process from biomass to biofuel is necessary in order to amplify bagasse as a renewable source. The delicate problem for second-generation biofuel production is the optimization of pretreatment technologies, which may include hydrothermal, dilute acid, steam explosion, alkaline and organosolv. Although it is costly, the pretreatment of bagasse has been reported to facilitate up to 90% conversion of sugars to ethanol compared to 20% without pretreatment for acid hydrolysis.[14]

## 2 Sugarcane in Top Producing Countries

Originally from Asia, sugarcane can be found in most tropical and subtropical climates. As of 2013, the world sugarcane production accounted for approximately 1900 million metric ton with the top countries located in Latin America and Asia. [6,15] Brazil being first (~40%), India second (~19%) , China third (~7%), Thailand fourth (~5%), Mexico sixth (~2.5%) and Colombia seventh (~1.5%) in global production rankings. Argentina has increased its average sugarcane growth over the last few years and now contributes to 1.1% of world production.[16] Table 1 shows the most recent approximate sugarcane crop production in different countries.

The majority of Colombian sugarcane plantations are located around the Cauca River Valley, and grow all year round with the potential to produce around 954 000 L $d^{-1}$ of ethanol from sugarcane juice.[17] This would represent the second largest ethanol producer in Latin America with all bioethanol coming from sugarcane.[17, 18] Sugarcane plantation in Cauca River Valley in Colombia is harvested on around 200,000 ha of land and it is estimated that the country can potentially generate 3.8 million L $d^{-1}$ of fuel ethanol by 2020.[19] In Mexico, sugarcane is harvested through manual cutting once a year in a period between December and May.[20] Although Mexico is known for sugarcane crops, sugarcane yields decreased from 72 to 64 metric ton $ha^{-1}$ annually in the last decade, which was attributed primarily to climate change.[21] Cuba used to be one of the largest exporters of sugar in the world with its main export market being the United States until the commercial trade blockage in the early 1960s. Cuba turned to the Soviet Union and Eastern European countries for trade but eventually lost these markets in 1991 due to the collapse of communism. Since then sugarcane production has significantly declined from 80 million metric ton $yr^{-1}$ to 24 million metric ton $yr^{-1}$ from 1991 to 2004. In 2005 it declined to 11.6 million metric ton $yr^{-1}$ following the trend observed in the preceding years.[22] However, Cuba has a great potential for sugarcane production and energy derived from sugarcane agricultural residues is under review.[23] Argentina, on the other hand, has its production limited to the northern, fertile, warm crop areas. Argentina typically uses the flat region in northern parts of the country, typically referred to as the pampas, due to the very fertile land and moderate warm climate that permits year round crop growth. Production is located on 320,000 ha of land.[16] Brazil is the leading country in sugarcane crop production with an estimated 55% of sugarcane transformed into ethanol, which yields an average of about approximately 68 liters per metric ton of sugarcane.[18] As of 2013, India is the second biggest producer of sugar in the world (27%).[24] Its cane is planted throughout three seasons (spring, summer and fall) in the northwestern region, with fall's duration being 12-14 months and its cultivation yielding higher amounts of cane and sugar recovery.[25] Thailand has been growing its sugarcane productivity significantly since 2004, a growth average of 53% from 2004 to 2013. This growth has placed Thailand as the fourth largest producer of sugarcane in the world with 51 functioning mills, 100 thousand farmers on 1.6 million ha of land.[15]

## 3 Sugarcane Agricultural Characteristics

Sugarcane belongs to the family *Poaceae* of the genus *Saccharum*. Its taxonomy and nomenclature have been difficult to record over the years but essentially the genus *Saccharum (S.)* consisting of six species known as *S. officinarum*, *S. spontaneum*, *S. robustum*, *S. sinense*, *S. barberi*, and *S. edule*, and some of its agricultural characteristics are shown in Table 2. Among the sugarcane species, *S. officinarum* contains high sucrose however it has poor resistance to disease. *S. spontaneum* is highly adaptable and may grow in various altitudes in tropical and subtropical climates. Due to the susceptibility to some diseases found in the most common specie (*S. officinarum*), breeding methods of sugarcane have been developed. In the last three to four decades, one of the major contributions of breeding sugarcane has been to produce higher sugar yield. Hence there have been modification in sugarcane chemical composition, for example the breeding varieties from 2011 had higher lignin and ash content than that of 2009, potentially leading to lower glucose yield.[26] Currently, there are numerous genetic breeding efforts such as simple sequence repeat and marker-assisted selection[27] where hybrid sugarcane plants have been derived from the crossing of *S. officinarum* and *S. spontaneum* for commercial purposes.[6, 28]

### 3.1 Sugarcane Processing

After growing for 12-16 months, sugarcane is cut for collection. Manual harvest involves burning the crop for collection, which facilitates the cutting process. This collection method is still used although many companies are projected to utilize mechanized harvesting of green sugarcane due to worker safety and environmental concerns.[29] Mechanical cutting does not involve burning the cane before collection, however it presents some operational challanges.[29] It has been highly adopted since it replaces the labor of up to 100 workers per farm in manual harvest.[30] In most recent studies, the state of Sao Paulo in Brazil used the green-harvest system for the cane, which accounted for 65.2% of the harvesting method and is expected to banish the burning harvest by 2029.[31]

Mechanical cutting does not permit the cane to be washed because the loss of sucrose is higher; hence mills use a dry wash process (i.e., jets of air). The chopped sugarcane is then placed in a shredder with the objective of opening the cells containing sugars and facilitating the sucrose extraction process. Grinding is an extraction process, which results in juice extraction and the agriculture residue, bagasse. Usually the first batch of juice extracted goes to sugar manufacturing and about 55%[32] goes to ethanol production. Sugarcane is usually cultivated for six years before replanting.[20] Sugarcane maturity, harvesting method, type of soil and efficiency of equipment used for the extraction process may affect the composition of sugarcane bagasse.

## 4 Pretreatment of sugarcane bagasse

The conversion of bagasse to biofuels has been actively studied using both the biological and thermal platform. One of the most promising pathways is second-generation cellulosic ethanol as summarized in Figure 1. Pretreatment is one of the major steps in the biological conversion of bagasse to bioethanol as it reduces its recalcitrance. It can be accomplished using biological, chemical, physical, or various combinations of these treatments. The reduction in recalcitrance has been attributed to several factors including changes in the interactions of hemicellulose, cellulose and lignin, increases in cellulose accessibility, removal of lignin-carbohydrates complexes and possible reductions in cellulose crystallinity in the plant cell wall. These effects increase sugar yields from cellulose thereby increasing ethanol fermentation yields provided fermentation inhibitors are managed. A variety of pretreatments have been used in recent studies for sugarcane bagasse as summarized in Table 3.

Steam explosion is a physico-chemical pretreatment prevalently used in sugarcane industry due to its low environmental impact and cost.[8, 33] It is a process in which the lignocellulosic materials in sugarcane bagasse are exposed to hot steam and pressure followed by explosive decompression of bagasse that results in lignin rearrangement due to partial hemicellulose hydrolysis and lignin solubilization due to high temperatures.[34] Enzymatic hydrolysis is also facilitated by changes in cellulose crystallinity and degree of polymerization caused by steam explosion.[35]

Hot water pretreatment of bagasse is environmentally beneficial as there is reduced deterioration of polysaccharides, and consequently lower inhibitor generation.[36] The disadvantage to this pretreatment is the high volume of water consumption and energy costs. This method generally employs temperatures ranging from 120-230 °C for 1-80 min and may recover 55 to 84% of hemicelluloses.[37-39] However, shorter periods of time ranging from 1-20 min and temperatures lower than 200°C are more commonly used so to minimize changes in lignin and cellulose.

The extrusion process is a physical pretreatment method that utilizes irradiation, and comparable to other treatments, targets the degradability of lignocellulosic materials for the enhancement of enzymatic hydrolysis. Such irradiation treatment for sugarcane bagasse comes in the form of microwaves, ultrasound and gamma rays.[33, 40] Gamma rays increase cellulose crystallinity as well as surface area, whereas microwave and ultrasound irradiation, given adequate conditions, decrease cyrstallinity of cellulose.[33, 40, 41]

Acid hydrolysis is efficient in breaking down hemicellulose and maximizes sugar yield from bagasse. It is a commercial method adopted by many researchers however the cost is claimed to be higher than that of liquid hot water pretreatment.[37] Dilute acid and concentrated acid are two types of acid hydrolysis. Dilute acid usually uses less than 10% acid concentration while concentrated acids is greater than 10%.[42] Acids such as sulfuric and phosphoric acid help to solubilize hemicelluloses and transform them into fermentable sugars.[43] In sugarcane bagasse pretreatment using sulfuric acid with 0.5% concentration at 121ºC during 60 min yielded 24.5 g $L^{-1}$ of total sugar after cellulose hydrolysis.[13] The use of hydrochloric acid has also been studied at 130ºC, 1.25% HCl concentration for 10 min resulting in 76.6% sugar release after 72 h of enzymatic hydrolysis.[44]

Organosolv pretreatment of sugarcane bagasse mainly utilizes ethanol (EtOH) and water as an organic solvent mixture.[33] The $\alpha$-aryl ether linkages of lignin are reactive under these conditions and are hydrolyzed and solubilized. This process is convenient for small mills because of its ease of recovery method and sulphur free discharge[37] but remains costly.[33] When bagasse was mixed with 60:40 EtOH/water with 5% dosage of acetic acid at 190ºC for 45 min, sugar yield reached 85.4% after 72 h of enzymatic hydrolysis.[45]

Alkaline pretreatments of bagasse promote the separation of cellulose and are efficient in the removal of lignin. The alkali usually causes a swelling in the biomass, which allows for the decrease in cellulose crystallinity. In contrast to other pretreatments, this particular process works at low reaction pressures, temperatures and concentration, which can be linked to reduce fermentation inhibitors and low cost.[46] However, its biggest disadvantage is associated to the difficulty of alkali recovery. A sodium hydroxide pretreatment (i.e. 110ºC for 1 h and 0.18% of NaOH) of bagasse has been shown to result in 77.3% sugar release after 72 h of enzymatic hydrolysis.[44]

Ionic liquids are salts composed of anions and cations of organic compounds, which are poorly organized making them have a melting point below 100 ºC.[47] These solvents have great thermal stability, non-volatility[48] and are exceptional catalysts for the delignification of bagasse.[49] Among different ionic solvents, most commonly used for sugarcane bagasse is 1-ethyl-3-methylimidazolium acetate ([Emim][Ac]), which has been reported to be very effective in dissolving cellulose.[50] Other solvents used for pretreatment of bagasse that have been reported include 1-butyl-3-methylimidazolium acetate ([Bmim][Ac]), 1-allyl-3-methylimidazolium chloride ([Amim][Cl]), 1-butyl-3-methylimidazolium chloride ([Bmim][Cl]) and 1,3-dimethylimidazolium dimethyl phosphate ([Mmim][DMP]).[48, 51, 52] These ionic liquids can remove up to 60% of lignin in sugarcane bagasse along with decreasing the crystallinity of cellulose fibers.[53] It has been reported that a 1:20 solution of bagasse to ([Mmim][DMP]) at 120 ºC for 120 min resulted in 70.38% of sugar conversion after 48 h of enzymatic hydrolysis.[52]

## 5 Sugarcane Bagasse Constituents and Characteristics

### 5.1 Cellulose Structure

Cellulose is a homopolysaccharide chain composed of anhydroglucose units linked by $\beta$-(1,4)-glycosidic bonds (Figure 2) which form a crystalline structure due to extensive intra- and intermolecular hydrogen bonds that facilitates its aggregation into fibrils.[54] The average molecular weight of sugarcane bagasse cellulose ranges from 157800-168400g $mol^{-1}$ [50] and the size of its cellulose fibers range from 1.0-1.5 mm.[55] A cellulose unit, known as elementary fibril, can be coated with other non-cellulosic polysaccharides to form micro-fibrils, which can then be cross-linked by hemicellulose matrices to form macro-fibrils, which creates resistance to chemical and enzymatic degradation.

Degree of polymerization pertains to the number glucose units in the molecular polymer and it can influence the effectiveness of enzymatic hydrolysis. The average degree of polymerization ($DP_w$) in sugarcane bagasse cellulose ranges from 974-1039.[50] DPw varies under different cellulose isolation methods and is dependent on the intrinsic viscosity ($\eta$). Intrinsic viscosity is the measure of volume occupied by the macromolecule and their ability to disturb flow (Table 4).[56] When sugarcane bagasse was subjected to delignification and potassium hydroxide isolation the $DP_w$ was 1406.5 while the combination of acetic and nitric acid lowered $DP_w$ to 822.5, indicating that the acetic and nitric acid mixture degrades the macromolecule of cellulose more than potassium hydroxide.[56]

The predominant polymorph of cellulose is known as cellulose I and can be detected through X-ray diffraction (XRD) and solid state cross polarization magic-angle spinning carbon-13 nuclear magnetic resonance (CP/MAS $^{13}$CNMR) spectroscopy.[56] XRD is one of the most commonly used techniques for crystallinity index (CrI, %) analysis[57, 58] and it showed that the untreated bagasse contains an average CrI of 56.7%. Table 4 shows the CrI of untreated commercial sugarcane bagasse. This index is frequently used to determine relative quantity of crystalline material present in sugarcane bagasse. CP/MAS $^{13}$CNMR has shown to be extremely resourceful in the morphological modifications analyzed in cellulose throughout hydrolysis, where the 64.8 ppm chemical shift corresponds to the C-6 crystalline cellulose signal and this is ratioed to 62.4 ppm signal for the C-6 amorphous of cellulose.[56]

### 5.2 Hemicellulose Structure

Hemicellulose is a heteropolysaccharide of low molecular weight. It averages 7380g $mol^{-1}$ in bagasse.[59] Sugar composition of hemicellulose in bagasse is primarily galactose (11.5-39.9%), xylose (15.5-28.9%) and glucose (17.5-50.5%) with smaller amounts of arabinose (5.35-14.31%), mannose (0.0-14.0%), rhamnose (2.5-10.6%) and uronic acids (1.0-2.3%).[60] Hemicellulose in sugarcane bagasse is composed of $\beta$-(1→4)-xylo-pyranose backbone, having about 200 $\beta$-xylopyranose residues linked by 1,4-glycosidic bonds, glucomannas and galactomannans, xyloglucans, $\beta$-glucans and small amounts of uronic acids.[61, 62] The degree of branching in hemicellulose is given by the arabinose/xylose ratio; hence, the lower the ratio the higher the degree of polymerization and likewise the higher the ratio the shorter the polymer chain.[60] Values for the arabinose/xylose ratio are approximately 0.2 for bagasse.[59, 63] Hemicellulose is linked to lignin by covalent bonds, whereas the linkage between hemicellulose and cellulose is by the way of hydrogen bonds, which integrate easily with one another creating stability and flexibility.[64] In sugar cane the hemicellulose content is found to be low, on average 19.90%,[65] compared to that of sugarcane bagasse which is approximately between 30-35%.[13] There are many methods of extraction of hemicellulose such as autohydrolysis,[66] active oxygen species (oxygen and hydrogen peroxide) and solid alkali, [61] and alkaline peroxide. [67, 68] In general, isolation comes from multiple alkaline extractions causing the cleavage of ester linkages and extracting the hemicellulose from the lignocellulosic matrix. Potassium hydroxide and sodium hydroxide with hydrogen peroxide pretreatments for hemicellulose isolation have shown high values for xylose, 83.1-84.6 and 85.02%, respectively.[59, 68] In comparison, dewaxed and distilled water, and water with solid alkali precooking resulted in much lower xylose yields, 55.20 and 57.43%, respectively (Table 5).[59, 61]

Structural changes in bagasse hemicellulose after isolation are typically analyzed using FTIR and $^{13}$C NMR.[59, 61, 63] FTIR has indicated complete rupture of ester bonds when under alkali pretreatment conditions (10% KOH with 20ºC, 35ºC and 50ºC).[68] $^{13}$C NMR was able to detect strong signals indicating the presence of 1,4-linked $\beta$-D-Xyl$p$ units and the 4-O-methoxyl group of glucuronic acid residues in xylan.[59, 61] It was concluded that $\beta$-D-Xyl$p$ units was the main component in bagasse hemicellulose.[61]

### 5.3 Lignin Structure

Lignin, the most abundant aromatic polymer, is an amorphous three-dimensional phenolic biopolymer. The biosynthesis of lignin could be considered to arise from polymerization of three types of phenylpropane units as the monolignols: *p*- coumaryl, sinapyl and coniferyl alcohols that allows for the rigid form (Figure 3). These monolignols can then give rise to the p-hydroxyphenyl (H), syringyl (S), and guaiacyl (G) lignins units.[51] Lignin in bagasse has a molecular weight average range of 507-3973mol g$^{-1}$.[69] Lignin in sugarcane is extremely low, average of 2.37%[70] and 4.16%[65], compared to ~25% found in sugarcane bagasse. Additionally, it has been reported that lignin content in sugarcane genotype IACSP04-627 to be 8.12% and IACSP04-065 to be 4.32%.[71] Table 6 shows the lignin content in different sugarcane bagasse.

Lignin affects most pretreatment methods as well as enzymatic hydrolysis, thus multiple studies have being made for structural information of lignin, such as ionic liquid, ammonia, dilute acid, etc.[51, 56] Isolation methods for bagasse such as pyrolysis coupled to gas chromatography-mass spectrometry (Py-GC/MS) showed that both coumaric and ferulic acid play an important role in the structure of bagasse accounting for 63%lignin compounds.[72-74] The $\gamma$-OH acylation of lignin side-chain by $p$-coumarates indicating that $p$-coumarates are primarily attached to the lignin polymer. Ferulates however, showed acylation of arabinosyl residue from arabinoxylan chains revealing that ferulates are generally linked to carbohydrates in the cell-wall.[72] Ionic liquid and hot water pretreatment both hydrolyzed the $\beta$-O-4 inter-unit links.[51, 69] Different methods for lignin isolation in sugarcane bagasse were efficient for lignin extraction processes showing the cleavage of $\beta$-O-4' linkages such as: dilute acids followed by steam explosion and ethanol washing, as well as alkali followed by steam explosions.[69] Proton, carbon, phosphorus and two-dimensional heteronuclear single quantum coherence Nuclear Magnetic Resonance ($^{1}$H, $^{13}$C, $^{31}$P and 2D HSQC NMR) are primarily used to identify the functional groups in the isolated lignin structure.[51, 69] An assessment of various hydroxyl groups in organosolv lignin, with results S-OH: 0.58 mmol $g^{-1}$, G-OH:0.47, H-OH:0.53 among others, can be obtained using $^{31}P$ NMR spectra.[75] The 2D HSQC NMR is able to approximately determine the carbohydrate complexes of lignin that $^{1}H$, $^{13}C$ and $^{31}P$ NMR are not able to detect due overlapping in signals.[51] Isolated lignin from sugarcane bagasse was reported to be composed of 83% of $\beta$-O-4' links, alkyl-aryl ether bonds, and very few quantities, 6% of $\beta$-5, phenylcoumarans; and, molar ratio of H:G:S was confirmed to be 2:38:60 respectively,[72] concluding bagasse is S-rich (Table 7). According to del Río *et al.*[8] the lignin of bagasse is derived from mature stem and therefore is rich in syringyl (S) lignin, which is present in mature tissue. The conclusions indicated that lignin from sugarcane bagasse is mainly composed of $\beta$-O-4' alkyl-aryl ether linkages.

### 5.4 Ash and extractives

The by-product of sugarcane bagasse after it is used for fuel in plants cogeneration systems is bagasse ash. Sugarcane bagasse ash is black in color and contains 2.39g $cm^{-3}$ of particle density with irregular shaped particles.[76] It contains about 87.8% of sand with particles sizes greater than 63$\mu$m, 11.50% of slit with particles sizes ranging from 2 to 63$\mu$m, 0.7% of clay with less than 2$\mu$m and 10.32% of organic matter.[76, 77] In Brazil, sugarcane bagasse ash generation was estimated to be approximately 2.5 million tons per year and is discarded primarily as soil fertilizer.[77] Economical and technological development for the application of ash have grown in the past few years. Ash from bagasse is rich in silica and hence may be used for recycling purposes such as ceramic raw material, additive to cement, concrete and fine aggregate in mortars.[77, 78] XRD has been used to determine the inorganic oxide content in bagasse ash (Table 8).[76-78]

Extractives in sugarcane bagasse range from 2.3-10.5% of total chemical composition.[79] These extractives are hydrophobic and can be fatty acids, waxes, and proteins, among others.[79, 80] Research has reported that about 0.9% of acetone extractives contained about 140 mg $k^{-1}$ of $n$-fatty acids, 700 mg $k^{-1}$g of $n$-aldehydes and 330 mg $k^{-1}$ of $n$-fatty alcohols in bagasse.[79] For chemical analysis purposes, extractives are usually removed from sugarcane bagasse. However, extractives may be a great source of value in major-scale biorefineries for cellulosic ethanol production from bagasse.[9]

## 6 Biomass to bioethanol

Efficient hydrolysis of the sugarcane bagasse along with the subsequent fermentation of sugars creates a compelling commercial opportunity. According to Linoj *et al.*[81] sugarcane encompasses two thirds of the production of sugar in the world. The advantages of biorefining sugarcane bagasse to bioethanol would include an ease of production when integrated into a sugarcane ethanol existing mill, hence lowering any necessary investments.

### 6.1 Sugarcane Bagasse to Bioethanol

A study presented by Walter *et al.* showed that if 76% of bagasse is pretreated and enzymatically hydrolyzed for sugar, this sugar could be fermented to yield up to 149.3

liters of ethanol per ton of bagasse.[82] Other studies suggest that in a two step pretreatment using a dilute acid pretreatment condition at 175ºC for 40 min and 1% $H_2SO_4$ concentration with a 1:1 solid liquid ratio, followed by an organosolv treatment, it is possible to achieve 192 liters of ethanol per ton of bagasse. Whereas using similar conditions, 120ºC for 40 min with 1% $H_2SO_4$ concentration with a 1:4 solid liquid ratio followed by organosolv, ethanol generation could produce up to 180 liters of per ton of sugarcane bagasse.[83] Different pretreatments and pathways for hydrolysis and fermentation have varying effects on glucose concentration available for fermentation contributing to different ethanol production (Table 9).

Cogeneration systems are very common in sugar mills.[23, 84] When using cogeneration systems for first and second generation production simultaneously in different boiler pressures (2.2-9.0 MPa), it was shown that the system using 2.2 MPa achieved a maximum yield of anhydrous ethanol production of 113.7 liters per ton of sugarcane.[85] According to Dias *et al*.[86] the double-effect distillation process of sugarcane bagasse is compared to conventional distillation. In the double-effect process, the distillation columns operates under vacuum pressures ranging from 19-25 kPa and the rectification columns pressure ranges from 101-135 kPa with an extractive distillation process using monoethyleneglycol (MEG) for ethanol dehydration, providing higher yields of anhydrous ethanol from bagasse than conventional (Table 10). Hemicellulose pentoses, mainly xylose and arabinose, are difficult to transform for the production of second-generation bioethanol, hence metabolic microorganisms are necessary to succeed on pentose.[66] Thus, pretreatment of bagasse is necessary in order to modify chemical composition, size and structure in such manner in which hydrolysis can be carried out promptly and with increased yields.

## 7 Biomass to Biopower

Power generation in the world is another cause of increased pollution and climate changes. Countries are seeking renewable energy sources for electricity production for the foreseeable future. In 2009, the Energy Information Administration (EIA) compared renewable electricity to net generation (Table 11) of the top 5 countries. Although China and United States are the leading net power generation countries, at 576.605 and 429.652 billion kWh respectively, currently, their renewable power energy profiles are less than 17% of the electricity generated. By contrast, Brazil and Canada have been more successful regarding renewable energy, producing 89.6% and 63.3%, respectively of the total energy produced from renewable sources, chiefly hydroelectric power.

Cogeneration systems generate electricity and thermal energy at high output capacities. In 2004 Cuba reached 600 MW of cogeneration capacity in the 85 sugarcane mills active.[22, 23] If 45 of the active 85 mills, which has a capacity of 4600-14000 ton of cane a day, were modernized cogeneration capacity would increase substantially to 1400-1600 MW.[22]

### 7.1 Sugarcane Bagasse to Biopower

Sugar and ethanol plants often utilize sugarcane bagasse as a source of fuel because it can produce enough power and heat to meet all needs. These plants are self-sufficient in energy consumption and often still have a surplus of bagasse which can present environmental concerns due to its prolonged on site accumulation, which poses a threat for higher spontaneous combustion possibility.[87] The mills in Brazil generate on average 12kWh of electricity per ton of sugarcane bagasse, 330 kWh of heat energy and 16kWh of mechanical energy.[84]

Steam-based sugarcane mills can be found in countries like Cuba and Brazil, which utilizes two types of steam turbines for low pressure steam and electricity production: Condensing Extraction Steam Turbine (CEST) and Backpressure Steam Turbine (BPST).[23, 88] CEST are high-pressure turbines used in sugar factories that are favored for pressure levels above 65 bar.[89] Any accessible residue from sugarcane processes such as lignocellulosic biofuel would be implemented for generating electricity. BPST, on the other hand, are non-condensing turbines, commonly found in refineries, in which exhaust steam at lower pressure loads and are usually cheaper than condensing turbines. BPST could generate up to 99.51 kWh per ton cane and fulfill electricity demand at the mills, while CEST could generate 121 kWh per ton cane, meet the energy demand at the mills and would export the surplus electricity, approximately 93 KWh per ton cane for public use (Table 12).[88] Alves *et al.*[88] also revealed that CEST yielded a surplus of electricity, unlike BPST because all available bagasse is consumed as fuel.

Gasification and Fischer-Tropsch (GFT) conversion process for sugarcane bagasse has been studied and concluded to be effective in energy efficiency for both liquid fuel production and overall energy when compared to other conversion process such as acid or enzymatic hydrolysis and saccharification and fermentation processes.[82, 83] Research studies by of Walter *et al.*[82] using sugarcane residues, trash and bagasse were analyzed for production of ethanol and electricity in terms of hydrolysis and gasification and Fischer-Tropsch processes. Multiple variables to avoid emissions of greenhouse gas emissions were hypothesized and it was concluded that GFT was slightly more feasible and effective where the estimated avoided emissions was 263.9 kg $CO_2$ equivalents per ton of carbon, with 67% from conventional ethanol production and 11% from surplus electricity production. While the same variables were taken into consideration in the hydrolysis process, the avoided emission was estimated to be 253.2 kg $CO_2$ equivalents per ton of carbon, with 94% from ethanol production and 6% from surplus electricity production. Another study determined that the avoided carbon dioxide emissions were larger for maximum ethanol production than that of the electricity production, concluding that a plant in which produces ethanol is more desirable then a plant that produces electricity using bagasse in order to avoid $CO_2$ emissions.[90] These processes are still under development and it is unknown which method is superior or more feasible and cost effective for a commercial scale.

## 8 Conclusions

Sugarcane is one of the most abundant crops in the world having innumerous mills and plants for sugar extraction and first generation ethanol production. Most Latin American countries possess tropical climates enabling them to generate sugarcane crops. Brazil alone is the greatest sugarcane producer utilizing ethanol for majority of its cars sold followed by Mexico and Colombia, and other countries with great potential for both bioethanol and biopower growth. Bagasse is a promising agricultural residue in the bioethanol production and power generation due its high cellulose and average lignin and hemicellulose content.

Pretreatment is one of the most crucial steps for ethanol production. Although there is not a specific pretreatment that is most used for commercial purposes and is cost-effective, the appropriate method of pretreatment followed by acid or enzymatic hydrolysis and fermentation is important for high yields in the conversion of sugars to ethanol. Commonly used are steam explosion, which is used for alteration of cellulose crystallinity and degree of polymerization, and dilute acid, which transforms a solubilized portion of hemicellulose into fermentable sugars. Similarly in power generation, specific processes have not been utilized in a commercial scope, CEST turbines and GFT conversion method appears to be promising due to its higher surplus electricity and hence energy efficiency.

## Acknowledgement:

The authors would like to thanks for their support of these studies through an NSF sponsored program titled “Effect of Thermal Treatment on Biomass and Hydrocarbons Production using Catalytic Pyrolysis Process/ NSF-CBET-1449404.”

References:

1. Hofsetz K, Silva MA. Brazilian sugarcane bagasse: Energy and non-energy consumption. *Biomass Bioenergy*. **46:**564-73 (2012).
2. Zhao Y, Chen M, Zhao Z, Yu S. The antibiotic activity and mechanisms of sugarcane (Saccharum officinarum L.) bagasse extract against food-borne pathogens. *Food Chem*. **185:**112-8 (2015).
3. Santos VEN, Ely RN, Szklo AS, Magrini A. Chemicals, electricity and fuels from biorefineries processing Brazil's sugarcane bagasse: Production recipes and minimum selling prices. *Renewable Sustainable Energy Rev*. **53:**1443-58 (2016).
4. Barrera I, Amezcua-Allieri MA, Estupiñan L, Martínez T, Aburto J. Technical and economical evaluation of bioethanol production from lignocellulosic residues in Mexico: Case of sugarcane and blue agave bagasses. *Chem Eng Res Des*.
5. Agency N. Biomass Opportunities in Colombia NL Agency Ministry of Foreign Affairs 2013.
6. Cheavegatti-Gianotto A, Abreu HMC, Arruda P, Bespalhok Filho JC, Burnquist WL, Creste S, et al. Sugarcane (Saccharum X officinarum): A Reference Study for the Regulation of Genetically Modified Cultivars in Brazil. *Trop Plant Biol*. **4:**62-89 (2011).
7. Ojeda K, Ávila O, Suárez J, Kafarov V. Evaluation of technological alternatives for process integration of sugarcane bagasse for sustainable biofuels production—Part 1. *Chem Eng Res Des*. **89:**270-9 (2011).

8. Soccol CR, Vandenberghe LPdS, Medeiros ABP, Karp SG, Buckeridge M, Ramos LP, et al. Bioethanol from lignocelluloses: Status and perspectives in Brazil. *Bioresour Technol*. **101:**4820-5 (2010).

9. Neves PV, Pitarelo AP, Ramos LP. Production of cellulosic ethanol from sugarcane bagasse by steam explosion: Effect of extractives content, acid catalysis and different fermentation technologies. *Bioresour Technol*. **208:**184-94 (2016).

10. Rabelo SC, Carrere H, Maciel Filho R, Costa AC. Production of bioethanol, methane and heat from sugarcane bagasse in a biorefinery concept. *Bioresour Technol*. **102:**7887-95 (2011).

11. Sindhu R, Gnansounou E, Binod P, Pandey A. Bioconversion of sugarcane crop residue for value added products – An overview. *Renewable Energy*.

12. Soetaert W, Vandamme EJ. Biofuels in Perspective. Biofuels: John Wiley & Sons, Ltd; 2009. p. 1-8.

13. Cardona CA, Quintero JA, Paz IC. Production of bioethanol from sugarcane bagasse: Status and perspectives. *Bioresour Technol*. **101:**4754-66 (2010).

14. Hamelinck CN, Van Hooijdonk G, Faaij APC. Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. *Biomass Bioenergy*. **28:**384-410 (2005).

15. Makul N, Sua-iam G. Characteristics and utilization of sugarcane filter cake waste in the production of lightweight foamed concrete. *Journal of Cleaner Production*. **126:**118-33 (2016).

16. Ferraro DO, Rivero DE, Ghersa CM. An analysis of the factors that influence sugarcane yield in Northern Argentina using classification and regression trees. *Field Crops Res*. **112:**149-57 (2009).

17. Delgadillo-Vargas O, Garcia-Ruiz R, Forero-Álvarez J. 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:**150-62 (2016).

18. Janssen R, Rutz DD. Sustainability of biofuels in Latin America: Risks and opportunities. *Energy Policy*. **39:**5717-25 (2011).

19. Quintero JA, Montoya MI, Sánchez OJ, Giraldo OH, Cardona CA. Fuel ethanol production from sugarcane and corn: Comparative analysis for a Colombian case. *Energy*. **33:**385-99 (2008).

20. Anaya CA, Huber-Sannwald E. Long-term soil organic carbon and nitrogen dynamics after conversion of tropical forest to traditional sugarcane agriculture in East Mexico. *Soil Tillage Res*. **147:**20-9 (2015).

21. Santillán-Fernández A, Santoyo-Cortés VH, García-Chávez LR, Covarrubias-Gutiérrez I, Merino A. Influence of drought and irrigation on sugarcane yields in different agroecoregions in Mexico. *Agricultural Systems*. **143:**126-35 (2016).

22. Alonso-Pippo W, Luengo CA, Koehlinger J, Garzone P, Cornacchia G. Sugarcane energy use: The Cuban case. *Energy Policy*. **36:**2163-81 (2008).

23. Alonso Pippo W, Garzone P, Cornacchia G. Agro-industry sugarcane residues disposal: The trends of their conversion into energy carriers in Cuba. *Waste Manage*. **27:**869-85 (2007).

24. Chagas ALS, Azzoni CR, Almeida AN. A spatial difference-in-differences analysis of the impact of sugarcane production on respiratory diseases. *Reg Sci Urban Econ*. **59:**24-36 (2016).

25. Kaur N, Bhullar MS, Gill G. Weed management options for sugarcane-vegetable intercropping systems in north-western India. *Crop Prot*. **74:**18-23 (2015).

26. Benjamin Y, Görgens JF, Joshi SV. Comparison of chemical composition and calculated ethanol yields of sugarcane varieties harvested for two growing seasons. *Ind Crops Prod*. **58:**133-41 (2014).

27. Barabaschi D, Tondelli A, Desiderio F, Volante A, Vaccino P, Valè G, et al. Next generation breeding. *Plant Sci*. **242:**3-13 (2016).

28. Jackson PA. Breeding for improved sugar content in sugarcane. *Field Crops Res*. **92:**277-90 (2005).

29. Viana KRO, Perez R. Survey of sugarcane industry in Minas Gerais, Brazil: Focus on sustainability. *Biomass Bioenergy*. **58:**149-57 (2013).

30. De Figueiredo EB, La Scala Jr N. Greenhouse gas balance due to the conversion of sugarcane areas from burned to green harvest in Brazil. *Agric, Ecosyst Environ*. **141:**77-85 (2011).

31. de Oliveira Bordonal R, Barretto de Figueiredo E, Aguiar DA, Adami M, Theodor Rudorff BF, La Scala N. Greenhouse gas mitigation potential from green harvested sugarcane scenarios in São Paulo State, Brazil. *Biomass Bioenergy*. **59:**195-207 (2013).

32. BNDES. Sugarcane-based bioethanol : energy for sustainable development / coordination BNDES and CGEE. 1 ed. Rio de Janeiro: BNDES; 2008.

33. Silva Ortiz P, de Oliveira Jr S. Exergy analysis of pretreatment processes of bioethanol production based on sugarcane bagasse. *Energy*. **76:**130-8 (2014).

34. Wanderley MCdA, Martín C, Rocha GJdM, Gouveia ER. Increase in ethanol production from sugarcane bagasse based on combined pretreatments and fed-batch enzymatic hydrolysis. *Bioresour Technol*.. **128:**448-53 (2013).

35. Aguiar RS, Silveira MHL, Pitarelo AP, Corazza ML, Ramos LP. Kinetics of enzyme-catalyzed hydrolysis of steam-exploded sugarcane bagasse. *Bioresour Technol*. **147:**416-23 (2013).

36. García JC, Zamudio, MA, Pérez, MA, López, F, Colodette, JL. Search for optimum conditions of paulownia autohydrolysis process and influence in pulping process. *Environ Prog*. **30:**92–101 (2011).

37. Vallejos ME, Zambon MD, Area MC, Curvelo AAdS. Low liquid-solid ratio fractionation of sugarcane bagasse by hot water autohydrolysis and organosolv delignification. *Ind Crops Prod.* **65:**349-53 (2015).

38. Vallejos ME, Felissia FE, Kruyeniski J, Area MC. Kinetic study of the extraction of hemicellulosic carbohydrates from sugarcane bagasse by hot water treatment. *Ind Crops Prod*. **67:**1-6 (2015).

39. Gao Y, Xu J, Zhang Y, Yu Q, Yuan Z, Liu Y. Effects of different pretreatment methods on chemical composition of sugarcane bagasse and enzymatic hydrolysis. *Bioresour Technol*. **144:**396-400 (2013).

40. Liu C-F, Ren J-L, Xu F, Liu J-J, Sun J-X, Sun R-C. Isolation and Characterization of Cellulose Obtained from Ultrasonic Irradiated Sugarcane Bagasse. *J Agric Food Chem.* **54:**5742-8 (2006).

41. Chen W-H, Tu Y-J, Sheen H-K. Disruption of sugarcane bagasse lignocellulosic structure by means of dilute sulfuric acid pretreatment with microwave-assisted heating. *Appl Energy*. **88:**2726-34 (2011).

42. Kumar S, Dheeran P, Singh SP, Mishra IM, Adhikari DK. Kinetic studies of two-stage sulphuric acid hydrolysis of sugarcane bagasse. *Renewable Energy*. **83:**850-8 (2015).

43. Saha BC, Bothast RJ. Pretreatment and enzymatic saccharification of corn fiber. *Appl Biochem Biotechnol*. **76:**65-77 (1999).

44. Yu Q, Zhuang X, Lv S, He M, Zhang Y, Yuan Z, et al. Liquid hot water pretreatment of sugarcane bagasse and its comparison with chemical pretreatment methods for the sugar recovery and structural changes. *Bioresour Technol*. **129:**592-8 (2013).

45. Zhang H, Wu S. Efficient Sugar Release by Acetic Acid Ethanol-Based Organosolv Pretreatment and Enzymatic Saccharification. *J Agric Food Chem*. **62:**11681-7 (2014).

46. Rabelo SC, Amezquita Fonseca NA, Andrade RR, Maciel Filho R, Costa AC. Ethanol production from enzymatic hydrolysis of sugarcane bagasse pretreated with lime and alkaline hydrogen peroxide. *Biomass Bioenergy*. **35:**2600-7 (2011).

47. Silveira MHL, Vanelli BA, Corazza ML, Ramos LP. Supercritical carbon dioxide combined with 1-butyl-3-methylimidazolium acetate and ethanol for the pretreatment and enzymatic hydrolysis of sugarcane bagasse. *Bioresour Technol*. **192:**389-96 (2015).

48. Sant'Ana da Silva A, Lee S-H, Endo T, Bon EP. Major improvement in the rate and yield of enzymatic saccharification of sugarcane bagasse via pretreatment with the ionic liquid 1-ethyl-3-methylimidazolium acetate ([Emim] [Ac]). *Bioresour Technol.* **102:**10505-9 (2011).

49. Long J, Li X, Guo B, Wang L, Zhang N. Catalytic delignification of sugarcane bagasse in the presence of acidic ionic liquids. *Catalysis Today*. **200:**99-105 (2013).

50. Bian J, Peng F, Peng X-P, Xiao X, Peng P, Xu F, et al. Effect of [Emim]Ac pretreatment on the structure and enzymatic hydrolysis of sugarcane bagasse cellulose. *Carbohydr Polym*. **100:**211-7 (2014).

51. Moghaddam L, Zhang Z, Wellard RM, Bartley JP, O'Hara IM, Doherty WOS. Characterisation of lignins isolated from sugarcane bagasse pretreated with acidified ethylene glycol and ionic liquids. *Biomass Bioenergy*. **70:**498-512 (2014).

52. Bahrani S, Raeissi S, Sarshar M. Experimental investigation of ionic liquid pretreatment of sugarcane bagasse with 1,3-dimethylimadazolium dimethyl phosphate. *Bioresour Technol*. **185:**411-5 (2015).

53. Siqueira G, Várnai A, Ferraz A, Milagres AMF. Enhancement of cellulose hydrolysis in sugarcane bagasse by the selective removal of lignin with sodium chlorite. *Appl Energy*. **102:**399-402 (2013).

54. Pu Y ZD, Singh PM and Ragauskas AJ. The new forestry biofuels sector. *Biofuels Bioprod Bioref*. **2:**58–73 (2008
).

55. Australian Government DoHaA, Office of the Gene Technology Regulator The Biology and Ecology of Sugarcane (Saccharum spp. hybrids) in Australia 2004. 6-7 p.

56. Sun JX, Sun XF, Zhao H, Sun RC. Isolation and characterization of cellulose from sugarcane bagasse. *Polym Degrad Stab*. **84:**331-9 (2004).

57. Pereira SC, Maehara L, Machado CMM, Farinas CS. Physical–chemical–morphological characterization of the whole sugarcane lignocellulosic biomass used for 2G ethanol production by spectroscopy and microscopy techniques. *Renewable Energy*. **87, Part 1:**607-17 (2016).

58. Saelee K, Yingkamhaeng N, Nimchua T, Sukyai P. An environmentally friendly xylanase-assisted pretreatment for cellulose nanofibrils isolation from sugarcane bagasse by high-pressure homogenization. *Ind Crops Prod*. **82:**149-60 (2016).

59. Sun JX, Sun XF, Sun RC, Su YQ. Fractional extraction and structural characterization of sugarcane bagasse hemicelluloses. *Carbohydr Polym.* **56:**195-204 (2004).

60. Peng F, Ren J-L, Xu F, Bian J, Peng P, Sun R-C. Comparative studies on the physico-chemical properties of hemicelluloses obtained by DEAE-cellulose-52 chromatography from sugarcane bagasse. *Food Res Int.* **43:**683-93 (2010).

61. Shi J-B, Yang Q-L, Lin L, Zhuang J-P, Pang C-S, Xie T-J, et al. The structural changes of the bagasse hemicelluloses during the cooking process involving active oxygen and solid alkali. *Carbohydr Res*. **359:**65-9 (2012).

62. Peng F, Ren J-L, Xu F, Bian J, Peng P, Sun R-C. Fractional Study of Alkali-Soluble Hemicelluloses Obtained by Graded Ethanol Precipitation from Sugar Cane Bagasse. *J Agric Food Chem*. **58:**1768-76 (2010).

63. Sukhbaatar B, Hassan EB, Kim M, Steele P, Ingram L. Optimization of hot-compressed water pretreatment of bagasse and characterization of extracted hemicelluloses. *Carbohydr Polym*. **101:**196-202 (2014).

64. Hamzeh Y, Ashori A, Khorasani Z, Abdulkhani A, Abyaz A. Pre-extraction of hemicelluloses from bagasse fibers: Effects of dry-strength additives on paper properties. *Ind Crops Prod*. **43:**365-71 (2013).

65. Andrade JL, Marcos; Otsuk, Ivani; Ferrari, Evaldo; Zimback, Léo; Possenti, Rosana Aparecida. Composição química de genótipos de cana-de-açúcar em duas idades, para fins de nutrição animal. *Bragantia*. **63:**341-9 (2004).

66. Baêta BEL, Lima DRS, Adarme OFH, Gurgel LVA, Aquino SFd. Optimization of sugarcane bagasse autohydrolysis for methane production from hemicellulose hydrolyzates in a biorefinery concept. *Bioresour Technol*. **200:**137-46 (2016).

67. Brienzo M, Siqueira AF, Milagres AMF. Search for optimum conditions of sugarcane bagasse hemicellulose extraction. *Biochem Eng J*. **46:**199-204 (2009).

68. Bian J, Peng F, Peng X-P, Xu F, Sun R-C, Kennedy JF. Isolation of hemicelluloses from sugarcane bagasse at different temperatures: Structure and properties. *Carbohydr Polym.* **88:**638-45 (2012).

69. Zeng J, Tong Z, Wang L, Zhu JY, Ingram L. Isolation and structural characterization of sugarcane bagasse lignin after dilute phosphoric acid plus steam explosion pretreatment and its effect on cellulose hydrolysis. *Bioresour Technol*. **154:**274-81 (2014).

70. C Cruz LRd, GeraseevLC, Carmo TnDd, Santos LDT, Barbosa EA, Costa GA, et al. Agronomic traits and bromatologic composition varieties of cane sugar. *Biosci J*. **30:**1779-86 (2014).

71. dos Santos AB, Bottcher A, Vicentini R, Sampaio Mayer JL, Kiyota E, Landell MAG, et al. Lignin biosynthesis in sugarcane is affected by low temperature. *Environ Exp Bot*. **120:**31-42 (2015).

72. del Río JC, Lino AG, Colodette JL, Lima CF, Gutiérrez A, Martínez ÁT, et al. Differences in the chemical structure of the lignins from sugarcane bagasse and straw. *Biomass Bioenergy*. **81:**322-38 (2015).

73. van der Pol E, Bakker R, van Zeeland A, Sanchez Garcia D, Punt A, Eggink G. Analysis of by-product formation and sugar monomerization in sugarcane bagasse pretreated at pilot plant scale: Differences between autohydrolysis, alkaline and acid pretreatment. *Bioresour Technol*. **181:**114-23 (2015).

74. Martínez PM, Punt AM, Kabel MA, Gruppen H. Deconstruction of lignin linked p-coumarates, ferulates and xylan by NaOH enhances the enzymatic conversion of glucan. *Bioresour Technol*.

75. da Silva CG, Grelier S, Pichavant F, Frollini E, Castellan A. Adding value to lignins isolated from sugarcane bagasse and Miscanthus. *Ind Crops Prod*. **42:**87-95 (2013).

76. Schettino MAS, Holanda JNF. Characterization of Sugarcane Bagasse ash Waste for Its Use in Ceramic Floor Tile. *Procedia Mater Sci*. **8:**190-6 (2015).

77. Faria KCP, Gurgel RF, Holanda JNF. Recycling of sugarcane bagasse ash waste in the production of clay bricks. *J Environ Manage*. **101:**7-12 (2012).

78. Almeida FCR, Sales A, Moretti JP, Mendes PCD. Sugarcane bagasse ash sand (SBAS): Brazilian agroindustrial by-product for use in mortar. *Construction and Building Materials*. **82:**31-8 (2015).

79. del Río JC, Marques G, Lino AG, Lima CF, Colodette JL, Gutiérrez A. Lipophilic phytochemicals from sugarcane bagasse and straw. *Ind Crops Prod*. **77:**992-1000 (2015).

80. Sheshmani S. Effects of extractives on some properties of bagasse/high density polypropylene composite. *Carbohydr Polym*. **94:**416-9 (2013).

81. Linoj KNV, Dhavala, P., Goswami, A., Maithel, S. Liquid biofuels in South Asia: resources and technologies. *Asian Biotechnol Develop Rev*. **8:**31–49 (2006).

82. Walter A, Ensinas AV. Combined production of second-generation biofuels and electricity from sugarcane residues. *Energy*. **35:**874-9 (2010).

83. Mesa L, González E, Romero I, Ruiz E, Cara C, Castro E. Comparison of process configurations for ethanol production from two-step pretreated sugarcane bagasse. *Chem Eng J*. **175:**185-91 (2011).

84. Turdera MV. Energy balance, forecasting of bioelectricity generation and greenhouse gas emission balance in the ethanol production at sugarcane mills in the state of Mato Grosso do Sul. *Renewable Sustainable Energy Rev*. **19:**582-8 (2013).

85. Dias MOS, Junqueira TL, Jesus CDF, Rossell CEV, Maciel Filho R, Bonomi A. Improving second generation ethanol production through optimization of first generation production process from sugarcane. *Energy*. **43:**246-52 (2012).

86. Dias MOS, Ensinas AV, Nebra SA, Maciel Filho R, Rossell CEV, Maciel MRW. Production of bioethanol and other bio-based materials from sugarcane bagasse:

Integration to conventional bioethanol production process. *Chem Eng Res Des*. **87:**1206-16 (2009).

87. Attard TM, McElroy CR, Rezende CA, Polikarpov I, Clark JH, Hunt AJ. Sugarcane waste as a valuable source of lipophilic molecules. *Ind Crops Prod*. **76:**95-103 (2015).

88. Alves M, Ponce GHSF, Silva MA, Ensinas AV. Surplus electricity production in sugarcane mills using residual bagasse and straw as fuel. *Energy*. **91:**751-7 (2015).

89. Ensinas AV MM, Nebra SA, Serra L. Reduction of irreversibility generation in sugar and ethanol production from sugar cane. . *Energy*. **34:**680-8 (2009).

90. Dias MOS, Junqueira TL, Cavalett O, Pavanello LG, Cunha MP, Jesus CDF, et al. Biorefineries for the production of first and second generation ethanol and electricity from sugarcane. *Appl Energy*. **109:**72-8 (2013).

91. García CA, Manzini F. Environmental and economic feasibility of sugarcane ethanol for the Mexican transport sector. *Sol Energy*. **86:**1063-9 (2012).

92. Clauser NM, Gutiérrez S, Area MC, Felissia FE, Vallejos ME. Small-sized biorefineries as strategy to add value to sugarcane bagasse. *Chem Eng Res Des*. **107:**137-46 (2016).

93. Mesa L, Morales M, González E, Cara C, Romero I, Castro E, et al. Restructuring the processes for furfural and xylose production from sugarcane bagasse in a biorefinery concept for ethanol production. *Chem Eng Process: Process Intensification*. **85:**196-202 (2014).

94. Gamberini MT, Gamberini MC, Nasello AG. Involvement of dopaminergic and cholinergic pathways in the induction of yawning and genital grooming by the aqueous extract of Saccharum officinarum L. (sugarcane) in rats. *Neurosci Lett*. **584:**270-5 (2015).

95. Rocha GJM, Gonçalves AR, Oliveira BR, Olivares EG, Rossell CEV. Steam explosion pretreatment reproduction and alkaline delignification reactions performed on a pilot scale with sugarcane bagasse for bioethanol production. *Ind Crops Prod*. **35:**274-9 (2012).

96. Mesa L, González E, Cara C, González M, Castro E, Mussatto SI. The effect of organosolv pretreatment variables on enzymatic hydrolysis of sugarcane bagasse. *Chem Eng J*. **168:**1157-62 (2011).

97. Liu CF, Sun RC, Zhang AP, Ren JL, Wang XA, Qin MH, et al. Homogeneous modification of sugarcane bagasse cellulose with succinic anhydride using a ionic liquid as reaction medium. *Carbohydr Res*. **342:**919-26 (2007).

98. Liu CF, Sun RC, Zhang AP, Ren JL. Preparation of sugarcane bagasse cellulosic phthalate using an ionic liquid as reaction medium. *Carbohydr Polym*. **68:**17-25 (2007).

99. Gurgel LVA, Marabezi K, Ramos LA, Curvelo AAdS. Characterization of depolymerized residues from extremely low acid hydrolysis (ELA) of sugarcane bagasse cellulose: Effects of degree of polymerization, crystallinity and crystallite size on thermal decomposition. *Ind Crops Prod*. **36:**560-71 (2012).

100. Laurito-Friend DF, Mendes FM, Reinoso FM, Ferraz A, Milagres AMF. Sugarcane hybrids with original low lignin contents and high field productivity are useful to reach high glucose yields from bagasse. *Biomass Bioenergy*. **75:**65-74 (2015).

101. Jackson de Moraes Rocha G, Martin C, Soares IB, Souto Maior AM, Baudel HM, Moraes de Abreu CA. Dilute mixed-acid pretreatment of sugarcane bagasse for ethanol production. *Biomass Bioenergy*. **35:**663-70 (2011).

102. Torres da Silva G, Chiarello LM, Lima EM, Ramos LP. Sono-assisted alkaline pretreatment of sugarcane bagasse for cellulosic ethanol production. *Catal Today*.

103. Bahurudeen A, Santhanam M. Influence of different processing methods on the pozzolanic performance of sugarcane bagasse ash. *Cem Concr Compos*. **56:**32-45 (2015).

104. Renó MLG, Olmo OAd, Palacio JCE, Lora EES, Venturini OJ. Sugarcane biorefineries: Case studies applied to the Brazilian sugar–alcohol industry. *Energy Convers Manage*. **86:**981-91 (2014).

Table 1 Sugarcane production

| Sugarcane crops | Brazil[1] | Mexico[21, 91] | Colombia[17] | Argentina[16, 92] | Cuba[22, 23, 93] | India[25] | Thailand[15] | China[15] | World[15, 17] |
|---|---|---|---|---|---|---|---|---|---|
| Year | 2013 | 2012 | 2013 | 2010 | 2009 | 2012-2013 | 2013 | 2013 | 2013 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Average production (million metric ton $yr^{-1}$) | 743 | 42.5-44.6 | 21.5 | 19 | 11.6 | 341.2-350 | 100.1 | 125.5 | 1877.1-1911 |
| Average annual yield of sugarcane (metric ton $ha^{-1}$) | 120 | 65 | 108 | 56 | 22.4 | 70 | 62.6 | | - |

Table 2 Characteristics of major sugarcane species

| Reference: [6, 55, 94] | *S. officinarum* | *S. spontaneum* | *S. robustum* | *S. sinense* | *S. barberi* | *S.edule* |
|---|---|---|---|---|---|---|
| Culms thickness (cm) | 3.5-6 | ~4 | 2.0-4.4 | ~2 | ~2 | - |
| Height of plant (m) | 1-6 | 5 | 10 | 5 | 5 | - |
| Chromosome number | 2n=80 | 2n=40-128 | 2n=60-~200 | 2n=80-124 | 2=111-120 | 2n=60-80 |
| Classification | Noble canes | Wild species | Wild species | Ancient hybrid | Ancient hybrid | Wild species |

Table 3 Different pretreatment conditions for sugarcane bagasse

| Pretreatment | Operating Conditions | Reference |
|---|---|---|
| Steam explosion | 0.6-4.8MPa, 160-260°C, 15 min | [33, 95] |
| Hot water | 120-230 °C, 1-80 min | [37-39, 83] |
| Alkaline | 53.2-120 °C, 4-65.6 h | [33, 46] |
| Organosolv | 150-200°C, 30-90 min, 35-70% of solvent | [33, 37, 45, 83] |
| Dilute acid | 100- 120 °C, 40-120 min, 1.8%-10% of acid concentration | [42, 96] |
| Concentrated acid | 80 °C, 90 min, 18%-40% of acid concentration | [42] |
| Ionic Liquids | 60-140 °C, 5-360 min, 3-10% of solvent | [48, 50-52] |
| Dilute acid (1) + microwave heat (2) | (1) 1.56 % of acid concentration, 0.2M, pH 0.68<br>(2) 130-190 °C, 5-10 min, 2.45GHz, 900W | [41] |

Table 4 Degree of polymerization of isolated cellulose of sugarcane bagasse and crystallinity index of commercial type bagasse

| Cellulose of sugarcane bagasse | | | | | |
|---|---|---|---|---|---|
| | Cellulose A[a,56] | Cellulose B[b,40] | Cellulose C[97] | Cellulose D[98] | Cellulose E[99] |
| $DP_w$ | 822.5-1406.5 | 1858.1-2040.8 | 1277.0 | 1309.6 | 1356.0 |
| Intrinsic Viscosity ($\eta$, ml g$^{-1}$) | 256.3-415.6 | 534.1-631.6 | 378.0 | 387.2 | 399.5[c] |
| Molecular Weight (Mw, g mol$^{-1}$) | 133250-227850 | 301000-362600 | 206800 | 212150 | Not reported |
| Sugarcane bagasse commercial variety | | | | | |
| | SP79-1011[57] | RB867515[57] | SP81-325[57] | RB92579[57] | Bagasse E[99] |
| CrI % | 52.7 | 55.8 | 52.6 | 60.4 | 62.0 |

[a,b] range of 6 isolated cellulose of bagasse under different isolation conditions

[c, 56] intrinsic viscosity ($\eta$) calculated from $DP_w^{0.9}=1.65(\eta)$

Table 5 Content of neutral sugars and uronic acids of isolated hemicellulose from sugarcane bagasse

| Isolation of Hemicellulose | Xylose (%) | Arabinose (%) | Glucose (%) | Galactose (%) | Mannose (%) | Rhamnose (%) | Uronic Acids (%) |
|---|---|---|---|---|---|---|---|
| Dewaxed + distilled water [59] | 55.20 | 10.73 | 20.42 | 7.68 | 4.13 | 1.84 | 6.95 |
| NaOH [59] | 81.37 | 11.93 | 3.97 | 1.78 | 0.47 | 0.48 | 3.50 |
| NaOH + $H_2O_2$ [59] | 85.02 | 8.65 | 5.87 | 0.46 | Trace | Not detectable | 1.75 |
| $H_2O$ [a, 61] | 57.43 | 6.25 | 28.52 | 6.36 | - | - | 1.44 |
| $H_2O$ + KOH [a, 61] | 79.92 | 5.5 | 12.03 | 0.88 | - | - | 1.67 |
| KOH [b, 68] | 83.1-84.6 | 11.0-12.1 | 2.1-3.1 | 0.5-0.7 | - | - | 1.4-2.6 |
| $H_2O_2$ [c, 67] | 73.1-82.6 | 3.8-7.2 | 3.8-7.9 | - | - | - | 3.6-7.0 |

[a] precooked with $H_2O_2$ and MgO

[b] range composition of 7 isolated hemicellulose

[c] range composition of 19 isolated hemicellulose

Table 6 Lignin content in sugarcane bagasse from different variety of sugarcane

| | Lignin content in sugarcane bagasse (%) | | |
|---|---|---|---|
| Sugarcane variety | Klason lignin | Acid-soluble lignin | Total lignin[a] |
| Hybrid 140[100] | - | - | 21.5 ± 0.2 |
| Hybrid 321[100] | - | - | 20.2 ± 0.4 |
| Hybrid 58[100] | - | - | 18.6 ± 0.1 |
| Hybrid 146[100] | - | - | 18.6 ± 0.1 |
| Hybrid 89[100] | - | - | 16.8 ± 0.1 |
| PE-BR[b,101] | - | - | 21.1 ± 0.9 |
| NA-BR[c,9] | 19.7 ± 0.1 | 2.2 ± 0.2 | 21.9 ± 0.3 |
| Raw bagasse[69] | 25.9 ± 0.3 | 4.7 ± 0.3 | 30.6 ± 0.6 |
| Raw bagasse B[102] | 22.9 ± 0.7 | 0.06 ± 0.0 | 23.0 ± 0.7 |
| RB867515[72] | 17.8 ± 0.6 | 2.2 ± 0.2 | 20.0 ± 0.8 |

[a] sum of klason and acid-soluble lignin
[b] sugarcane bagasse from Pernambuco - Brazil
[c] sugarcane bagasse from Nova America - Brazil

Table 7 S:G:H ratio of lignin in sugarcane bagasse

| | Ball milled lignin[69] | Ethanol lignin[69] | Water soluble lignin[69] | Dioxane lignin[69] | Ball milled 2 lignin[72] | Whole cell wall lignin[72] |
|---|---|---|---|---|---|---|
| Lignin aromatic units | | | | | | |
| S (%) | 55.4 | 58.4 | 53.6 | 55.0 | 60.0 | 60.0 |
| G (%) | 39.1 | 30.5 | 32.5 | 38.3 | 38.0 | 37.0 |
| H (%) | 5.5 | 11.1 | 13.9 | 6.7 | 3.0 | 2.0 |
| S/G ratio | 1.4 | 1.9 | 1.6 | 1.4 | 1.6 | 1.6 |
| *p*-coumarate/ferulate ratio | 9.8 | 4.5 | 1.9 | 6.2 | 2.6 | 12.0 |

Table 8 Chemical characteristics of sugarcane bagasse ash

| (%) | Bagasse ash 1 [77] | Bagasse ash 2 [103] | Bagasse ash 3 [76] | Bagasse ash 4 [78] |
|---|---|---|---|---|
| $SiO_2$ | 61.59 | 72.95 | 85.55 | 80.2 |
| $Al_2O_3$ | 5.92 | 1.68 | 2.29 | 2.60 |
| $Fe_2O_3$ | 7.36 | 1.89 | 1.21 | 5.60 |
| $K_2O$ | 6.22 | 9.28 | 1.33 | 4.00 |
| CaO | 5.00 | 7.77 | 4.05 | 1.80 |
| MnO | 0.10 | - | 0.08 | 0.20 |
| $TiO_2$ | 1.46 | - | 0.20 | 1.40 |
| $SO_3$ | 0.42 | 4.45 | 2.28 | 0.10 |
| MgO | 1.17 | 1.98 | - | 1.60 |
| $P_2O_5$ | 0.98 | - | 3.01 | 1.40 |

Table 9 Ethanol yield from fermentation of SHF and SSF under different pretreatments

| | Parameters | | |
|---|---|---|---|
| Bagasse pretreatment | Initial glucose concentration (g $L^{-1}$) | Ethanol produced (g $L^{-1}$) | Ethanol yield (%, ethanol produced by gram of glucose) |
| Separate hydrolysis and fermentation (SHF) | | | |
| SEB[a,102] | 57.7 ± 1.4 | 25.6 ± 0.3 | 44.4 |
| SA-AWB6[b,102] | 50.1± 0.2 | 23.4 ± 0.2 | 46.6 |
| SA-AWSEB[c,102] | 50.1 ± 1.4 | 20.4 ± 0.1 | 40.8 |
| AH[d,9] | 57.8 | 25.2 | 43.6 |
| $H_3PO_4$[9] | 54.9 | 24.9 | 45.4 |
| $H_2SO_4$[9] | 54.9 | 20.1 | 43.7 |
| Simultaneous saccharafication and fermentation (SSF) | | | |
| AH[d, 9] | 54.9 | 18.8 | 34.2 |
| $H_3PO_4$[9] | 53.4 | 16.9 | 31.6 |
| $H_2SO_4$[9] | 48.2 | 18.4 | 37.2 |
| [a] Steam-exploded bagasse<br>[b] Sono-assisted alkali-washed bagasse<br>[c] Sono-assisted alkali-washed steam-exploded bagasse<br>[d] Autohydrolysis (Liquid hot water) bagasse | | | |

Table 10 Sugarcane juice and bagasse results from conventional and double-effect distillation processes

| Reference:[86] | Conventional distillation | Double-effect distillation |
|---|---|---|
| Anhydrous ethanol from bagasse (L $t^{-1}$ cane) | 18.8 | 22.0 |
| Anhydrous ethanol from sugarcane juice (L $t^{-1}$ cane) | 83.7 | 83.7 |

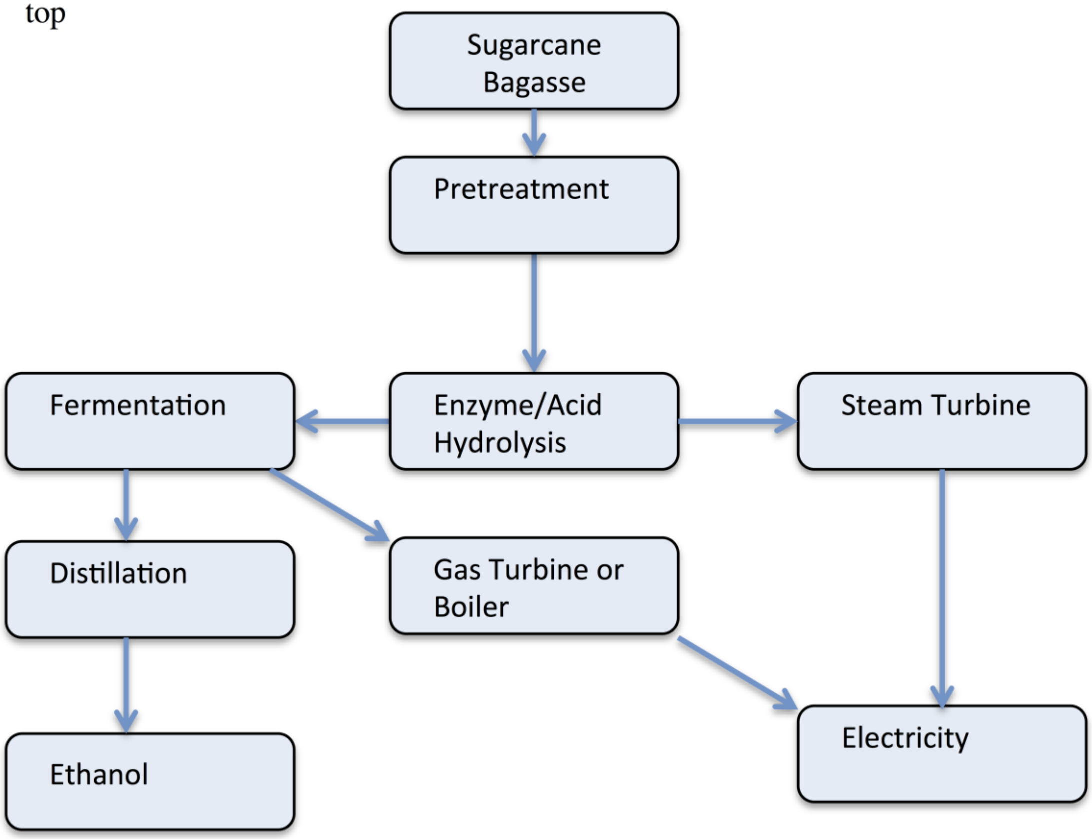
Table 11 Top 5 countries in electricity generation and its renewable use

| Reference: [1] | Generated electricity (billion kWh) | Renewable electricity % |
|---|---|---|
| China | 576.605 | 16.7 |
| USA | 429.652 | 10.9 |
| Brazil | 410.258 | 89.6 |
| Canada | 371.008 | 63.3 |
| Russia | 165.227 | 17.8 |
| World | 3760.590 | - |

Table 12 Electricity productions in BPST and CEST system

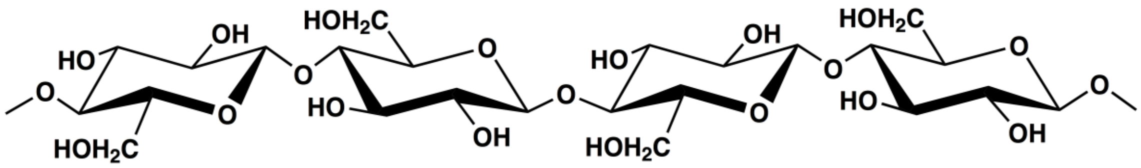
| System | BPST | | CEST | | | |
|---|---|---|---|---|---|---|
| Condition of turbine | 1.9MPa, 593K (7MW)[23] | 2.2-10MPa, 573-803K[88] | 6.0MPa, 754K[104] | 4.2MPa, 693K (38MW)[23] | 6.3MPa, 793K (30MW)[23] | 6.5-10MPa, 753-803K[88] |
| Electricity generated (KWh $t^{-1}$ cane bagasse) | 22.79 | 38.62-99.51 | 114.00 | 110.00 | 130.00 | 105.48-121.22 |
| Electricity surplus (KWh $t^{-1}$ cane bagasse) | - | 10.62-71.51 | 90.20 | 85.00 | 105.00 | 77.48-93.22 |

top

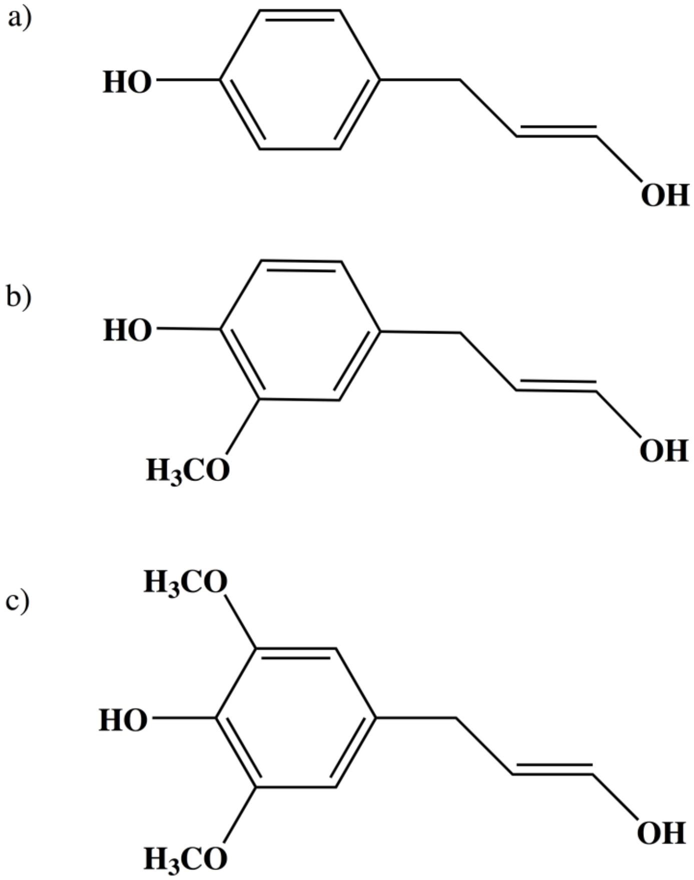


Tais L Bezerra Figure 1 Bioethanol and Biopower process from second-generation biomass

top



Tais L Bezerra Figure 2 Structure of Cellulose top



Tais L Bezerra Figure 3 Lignin structure with a) p-coumaryl alcohol b) Coniferyl alcohol and c) Sinapyl alcohol