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Sugarcane bagasse: Foreseeable biomass of bio-products and biofuel: An overview

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Abstract

Depleted supplies of fossil fuel, regular price hikes of gasoline, and environmental damage have necessitated the search for economic and eco-benign alternative of gasoline. Ethanol is produced from food/feed-based substrates (grains, sugars, and molasses), and its application as an energy source does not seem fit for long term due to the increasing fuel, food, feed, and other needs. Sugarcane is among the principal agricultural crops cultivated in tropical countries. The dry pulpy fibrous residue that remains after crush of sugarcane stalks is called Bagasse. It is Agroindustrial solid wastes which accumulated each day, causing big environmental problems. Sugarcane residues, particularly sugarcane bagasse (SB) and leaves (SL) have been explored for both biotechnological and non-biotechnological applications. For the last three decades, SB and SL have been explored for use in lignocellulosic bioconversion, which offers opportunities for the economic utilization of residual substrates in the production of bioethanol and value-added commercial products such as xylitol, specialty enzymes, organic acids, single-cell protein, etc. However, there are still major technological and economic challenges to be addressed in the development of bio-based commercial processes utilizing SB and SL as raw substrates. This article aims to explore SB and SL as cheaper sources of carbohydrates in the developing world for their industrial implications, their use in commercial products including commercial evaluation, and their potential to advance sustainable bio-based fuel systems.

Keywords: biofue; bioethanol; sugarcane residues; ethanol; xylitol; value added product

1. Introduction

The constant demand for non-food and feed based substrates has influenced the need to exploit sustainable and cheaper resources for their bioconversion into value-added products of commercial interest through basic routes of microbial bio-conversion (Hatti-Kaul *et al*., 2007) [11]. With this objective, there have been many products obtained from renewable resources such as biomass. Due to advancement in the agricultural industries, millions of tons of wastes and byproducts are generated every year that have potential as low-cost sources of energy and material (Pandey *et al*., 2000) [21]. One of these byproducts is sugarcane bagasse, which can be used in the production of industrial enzymes, ethanol, xylitol, organic acids, etc (Parameswaran, 2009) [22]. Bagasse is a residue obtained from sugarcane after it is crushed to obtain the juice used for sugar and ethanol production. Another important sugarcane residue is the leaves, which are usually left in agricultural fields during sugarcane harvesting (Krishna *et al*., 1998) [13]. The dried leaves, called sugarcane trash (ST), are produced in abundance (6–8 tons from one hectare of sugarcane crop) (Singh *et al*., 2008) [28]. Generally, leaves are burnt in the fields, which produces fly ash, severely damages soil microbial diversity, and raises environmental concerns.

Now in these days, the major feedstock used for liquid biofuel production depends on agriculture food crops. For example, corn, wheat, sugar beets, and sugar canes are widely used for bioethanol production. For biodiesel production, oil seeds such as soybean, rapeseed, sunflowers, and palm oil are also being used (Demirbas, 2008) [8]. The availability of these feed stocks differs from one region to another as a result of climatic factors. According to Ajanovic (2013) [3], the major feedstock used to produce bioethanol is wheat, which accounts for 70%, whereas the use of barley for bioethanol production accounts for just 15%, followed by 10% for corn, and 5% for rye of the total bioethanol production in the European Union in 2008. Rapeseed is used to produce 79% of the European Union’s biodiesel, where 18% of the production comes from soybean, and just 3% is based on sunflowers. Agroindustrial wastes included natural (organic) and non-natural of unwanted materials, produced mainly from agriculture operations (Sarkar *et al*., 2012) [25]. Solid Agroindustrial wastes are wastes in solid forms such as grape pomace, sugar beet pomace, potato starch residues, raw corn starch, sugarcane bagasse etc (Visioli *et al*., 2014) [30]. Furthermore, agricultural wastes can be sugar-containing residue such as sugarcane and starchcontaining residues (Visioli *et al*., 2014) [30]. Additionally, Agroindustrial wastes can be either degradable wastes or non-degradable (Rabi *et al*., 2009) [23].

In general, the biological process from converting the lignocellulose biomass to fuel ethanol involves: (1) pretreatment either to remove lignin or hemicellulose to liberate cellulose; (2) depolymerization of carbohydrate polymers to produce free sugars by cellulase mediated action; (3) fermentation of hexose and/or pentose sugars to produce ethanol; (4) distillation of ethanol. Ethanol produced from sugarcane residues is one of the most suitable alternatives for partial replacements of fossil fuels because it provides energy that is renewable and less carbon intensive than gasoline. Bioethanol reduces air pollution and also contributes to mitigate climate change by reducing greenhouse gas emissions. This paper reviews the important information on the sugarcane bagasse: foreseeable biomass of bio-products and biofuel**.**

2. Chemistry of sugarcane leaves and sugarcane bagasse

The complex chemical composition of the cell walls in SB limits its use as fodder for cattle and ruminants, in contrast to wheat straw, rice straw, sorghum straw, etc., which makes SB a more attractive substratefor commercialization. Generally, SB is composed (% w/w dry basis) of hemicellulose (26.2–35.8), cellulose (35–45), lignin (11.4–25.2), and others (2.9–14.4) (Zhao *et al*., 2009) [31]. The unequal chemical composition of bagasse depends upon multiple factors, including crop variety, climate conditions, location and mode of growth, use of fertilizers, and physical and chemical composition of soil (Canilha *et al*., 2011) [5]. The method of chemical composition analysis may also play a crucial role in establishing the chemical makeup of bagasse. In order to utilize the LB into value-added products, harnessing of cellulosics fraction into ready-to-fermentable sugars is inevitable (Zhao *et al*., 2009) [31]. It is evident that the high content of lignin in the plant cell wall is a major barrier to access the carbohydrate fraction of the cell wall, which essentially requires pretreatment (higher chemical loadings in conjunction with increased reaction time and temperature) and higher cellulase loadings result in an uneconomic process (Chandel *et al*., 2010) [7]. The costs of cellulolytic enzymes are high, and the required amount of cellulases is also high, which increases processing costs. The removal of lignin increases accessibility to cellulose and allows more amenability of cellulase to the carbohydrate skeleton of plant cell wall (Zhao *et al*., 2009) [31]. The low content of ash (1.4%) in SB was found to be highly advantageous over other agricultural residues such as rice straw (17.5% ash) or wheat straw (11.0% ash) (Pandey *et al*., 2010).

3. Sugarcane structure

Sugarcane is composed by stem and straw (or trash). Sugarcane stem is the material removed before the milling of cane to obtain a juice which is subsequently used for sugar (sucrose) or alcohol (ethanol) production. SB is the residue from stems after extraction of juice. SS (or trash) is composed by fresh leaves, dry leaves, and tops available before harvesting. Fresh leaves are green and yellow in color, tops are the part of cane plant between the top end and the last stalk node, and dry leaves are normally in brownish color (Neto, 2005) [18]. Potential uses of the leaves include: (1) as a fuel for direct combustion; (2) as a raw material for conversion by pyrolysis to char, oil, and/or gas; (3) as a raw material for conversion by gasification and synthesis to methanol. Potential uses for the tops include: (1) as a ruminant feed, either fresh or dried; (2) as a substrate for anaerobic fermentation to methane; (3) after reduction in water content, for the energy uses listed for cane trash (Triana *et al*., 1990) [29]. SB and SS are normally burnt in the open agricultural field after the harvesting of the crop, or in some cases, used as an untapped source of simple sugars that can be utilized for the alcohol production.

4. Physical and chemical compositions of sugarcane

Physically, sugarcane is constituted by four major fractions, whose relative magnitude depends on the sugar agroindustrial process: fiber, non soluble solids, soluble solids, and water (Figure 1). The fiber is composed of the whole organic solid fraction, originally found in the cane's stem, and characterized by its marked heterogeneity. The non soluble solids, or the fraction that cannot be dissolved in water, are constituted mainly by inorganic substances (rocks, soil, and extraneous materials), and it is greatly influenced by the conditions of the agricultural cane processing, types of cutting, and harvesting. Soluble solids fraction that can be dissolved in water are composed primarily of sucrose as well as other chemical components such as waxes, in a smaller proportion (Triana *et al*., 1990) [29]. SB or SS which are the focus of 2G ethanol production are lignocellulosic materials chemically composed by cellulose, hemicelluloses, and lignin.

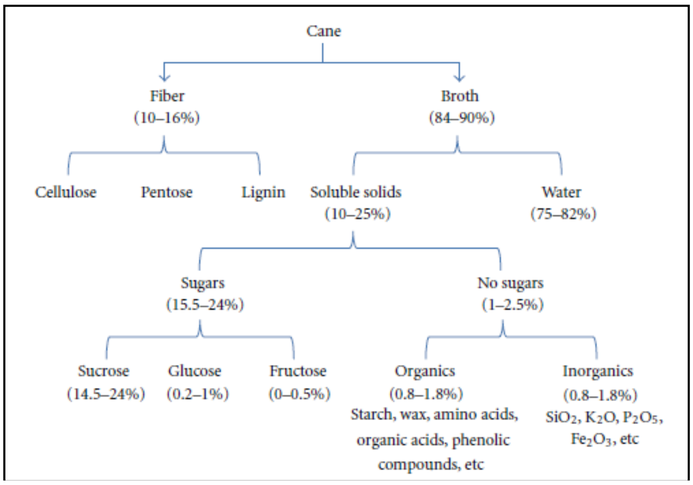

Fig 1: General composition of Sugarcane (Mutton, 2008) [16].

5. Pretreatment of bagasse for industrial uses

An effective pretreatment is to expose the cellulosics by removal of lignin or hemicellulose to improve the overall hydrolysis efficiency (Kumar *et al* 2009) [14]. In addition to pretreatment, an effective cellulolytic enzyme cocktail, the amount of enzyme loading, hydrolyzing conditions and the nature of lignocellulosic material are critical parameters for maximum hydrolysis of lignocellulosic material (Zhao *et al*., 2009) [31]. Substantial increase in lignin removal and hemicellulose depolymerization into simpler sugars has often been reported with pretreated substrate. Pretreated SB has also been utilized as an inert support material for fungal biomass in the solid-state fermentation process (Panday 1999) [20] and as an immobilization carrier (Santos *et al*., 2008) [24]. The mechanistic application of pretreated SB impregnated with suitable liquid media provides homogenous aerobic conditions throughout the bioreactor, which in turn will yield high product titers with relatively high purity after the completion of a cultivation cycle

6. Value-added products and sugarcane bagasse of commercial significance

6.1 Ethanol

SB has long been studied for industrial applications, including ethanol production. Theoretically, a single ton of SB could yield up to 300 L of ethanol (Cerqueira-Leite *et al*., 2009) [6]. However, there are several parameters that directly affect ethanol yield, such as the quality of bagasse and the process employed for ethanol production (Cerqueira-Leite *et al*., 2009) [6]. Separate hydrolysis and fermentation (SHF) and simultaneous saccharification and fermentation (SSF) have been implemented using SB for ethanol production (Chande *et al*., 2007) [7]. Santos *et al*. 34 obtained maximum cellulose-to-ethanol conversions (~60%) with volumetric productivity 0.29–0.30 $g\ L{-}1h^{-1}$ in pre-saccharification assisted SSF from SB. Dias *et al*. (2009) [9] suggested the importance of process integration in sugarcane processing mills. Under thermal integration, SB was hydrolyzed in an organosolv process catalyzed by dilute acid and then utilized for conventional production of ethanol from sugarcane juice. These studies revealed the use of SB and lignin as auxiliary fuels to fulfill the energy demands of the bio refinery.

6.2 Xylitol

D-xylitol is another value-added product that can be produced from SB/SL by microbial fermentation to cater for its large demand in food and pharmaceutical industries (Carvalho *et al*., 2008 and Prakasham *et al*., 2009) [1]. It is a five carbon sugar alcohol that is naturally found in various fruits and vegetables. Due to its anti-carcinogenicity, tooth rehardening and remineralization properties, D-xylitol has been widely applied in the pharmaceutical industry, odontological formulations, and in food industries (Prakasham *et al*., 2009) [2]. Being a sugar substitute, xylitol has been used in dietary foods especially for insulin-deficiency patients (Carvalho *et al*., 2008 and Prakasham *et al*., 2009) [1, 2]. Yeast species (mainly Candida sp.) have been known to produce xylitol from pentose-rich SB hydrolysates as reviewed by Prakasham *et al*. (2009) [2]. SB has also been found an excellent carrier for entrapping Candida guilliermondii cells for the continuous production of xylitol (Santos *et al*., 2008) [24]. SB has been reported on multiple occasions in research and development as potential substrate for xylitol production, however, the industrial output of xylitol from SB is yet to come.

6.3 Industrial enzymes

SB has been used for the production of industrial enzymes such as xylanase, cellulase, amylase, and laccase by certain bacteria and fungi, employing solid-state fermentation (SSF) or submerged fermentation (SmF) systems. Among others, cellulase and xylanase have been studied extensively for production from SB (Singh *et al*., 2010) [26]. Singhania *et al*. (2006) compared cellulase production from SB with production from other lignocellulosic materials such as wheat bran, cassava bagasse, and rice straw under SSF by Trichoderma reesei NRRL 11 460. The maximum production of cellulase (154.58 U gds^{-1}) was reported from SB, followed by wheat bran, cassava bagasse, and rice straw. The cost of cellulase plays a vital role in the success of biorefineries. A potential technology has yet to be investigated that can provide a feasible approach to the cost-effective production of cellulase with high titers.

7. Sugarcane bagasse derived microbial metabolic products of commercial interest

Apart from ethanol, xylitol, enzymes, and organic acids, SB has been employed to make other value-added products of commercial interest such as antibiotics, animal feed, biohydrogen, alkaloids, and pigments (Pandey *et al*., 2000) [21]. Nampoothiri and Pandey50 used SB to produce L-glutamic acid and reported a yield of 80 mg L^{-1} glutamic acid g−1 dry bagasse under an SSF system. The production of a single-cell protein with Candida langeronii RLJY-019 using SB has also been established under SmF cultivation (2009). SB has also been explored for the production of various organic acids (citric acid, lactic acid, gluconic acid, etc.) using different cultivation techniques and with a variety of microorganisms. Borges and Pereira (2010) [4] employed SB hemicellulosic hydrolysate for succinic acid production by Actinobacillus succinogenes. Singh *et al*. (2003) [27] used SB as an inert support for the growth of fungi Aspergillus niger mycelium for gluconic acid production under SSF and a semi-solid statefermentation (SmSF) system with a stabilized mutant strain ORS-4.410. A plant hormone, gibberellic acid (GA), was produced under SSF conditions by Gibberella fujikuroi, NRRL 2278 using SB. An excellent growth of biomass was observed, but only a trace amount of GA was noted during the fermentation reaction (Nampoothiri and Pandey, 1996) [17].

8. Bio-industrial significance of sugarcane leaves/trash

SL has yet to be explored for biological processes. The cell walls of SL are composed of 57.5% carbohydrate, demonstrating the potential for the bioconversion of products of commercial significance, including ethanolas biofuel. However, the abundance of lignin (36.1%) and silica (6.96%) may limit the industrial and veterinary acceptability of SL.61 Regardless of the complex chemical composition of its cell wall, SL was hydrolyzed by sulfuric acid at varying temperatures, acid loads, hydrolysis times, and solid: liquid ratios in a fractional factorial and central composite design. Krishna *et al*. (1998) [13] reported ethanol production (2% w/v) from SL employing SSF with cellulases from Trichoderma reesei QM 9414 and S. cerevisiaeNRRL-Y-132. Ferreira-Leitao *et al*. (2010) [10] evaluated the saccharification of SL into glucose (97.2% theoretical yield) after pretreatment with steam at 220 ◦ C for 5 min. Among products of commercial significance, Mane *et al*. (1988) [15] exploited ST for oxalic acid production (42.9–51.6% w/w) using a nitric oxide oxidation process. SL was explored for the development of a low-density biomass gasification system for thermal applications, (Jorapur and Rajvanshi, 1995) [12] and the efficacy of this system was assessed for more than 700 h ex situ, generating output levels of 288–1080 MJ h^{-1}.

9. Future perspectives

The byproducts generated during agro-industrial processing of sugarcane, SB and SL, constitute potential sources of carbohydrates that can be used to generate valuable products of commercial interest. Bio-industrial applications appear to provide sustainable, economic, environmental, and strategic advantages, with breakthroughs in micro-biotechnology offering huge potential opportunities. SB has already been successfully converted into many value-added products such as ethanol, xylitol, organic acids, industrial enzymes, and other important specialty chemicals. Scaling up to the pilot scale, however, is still a necessity. Such a step forward in the developing world would be highly rewarding. For instance, it has already been foreseen that 16 times more energy could be produced if the entire sugarcane plant were used by the alcohol industry, including SB in the process. The energy generation could be increased even more if SL were added to the processing cycle. The increasing price of gasoline may be remedied by SB-derived biofuel in the near future. In the sugar- and alcohol-producing industries, integration of process operations like hydrolysis, detoxification, fermentation, and distillation would be an effective strategy to maximize the efficient utilization of raw substrates. Currently, SB is mostly burned in boilers as a cheaper source of energy. The available technology for bioethanol production from SB polysaccharides cannot afford a competitive price for ‘second-generation ethanol’. Therefore, alternative processes to convert SB and SL/ST into value-added products of commercial significance such as xylitol, enzymes, organic acids, antibiotics, and single-cell protein would contribute to economizing the entire process.

Last three decades of vigorous developments in pretreatment technologies, microbial biotechnology, and downstream processing have made it reality to harness the sugarcane residues for the production of many products of commercial significance at large scale without jeopardizing the food/feed requirements. Biomass recalcitrance is a main challenge toward the successful exploitation of these residues. To overcome the biomass recalcitrance, pretreatment is an inevitable process to ameliorate the accessibility of carbohydrate for the subsequent enzymatic hydrolysis reaction to generate fermentable sugars. There are several robust pretreatment methods available; however, the ultimate choice for the selection of pretreatment process depends upon the effective delignification or hemicellulose removal, minimum generation of inhibitors, low sugar loss, time savings, being economic and causing less environmental pollution. The released sugars after enzymatic hydrolysis and hemicellulose depolymerization are converted into ethanol by the suitable ethnologic strain. In order to get desired ethanol yields, the ethnologic strains should have ability to utilize pentose and hexose sugars, inhibitor resistance, and high osmotolerance. The following ten requirements are pivotal in order to establish a long-term sustainable second-generation ethanol production process from sugarcane residues. (1) Fullest utilization of SB and SS generated in the country for the better management. (2) Selection of right pretreatment and detoxification strategy. (3) In-house cellulase production and development of cellulolytic strains and ethanol producing strains from pentose and hexose sugars showing inhibitor resistance, ethanol tolerance, and faster sugar conversion rates. (4) Process intensification: hydrolysis and fermentation together in one place. (5) Cheap, fast, and effective ethanol distillation. (6) Integration of bioethanol producing units with sugar/distilleries for the coutilization of machinery, reactors, and other equipment. (7) Maximum by products utilization (lignin, furans, and yeast cell mass). (8) Environmental protection.

10. Conclusion

Sugarcane bagasse (SB) and sugarcane leaves (SL) are the attractive second-generation renewable feedstock available in several countries like India. This feedstock if used judiciously may provide the sustainable supply of drop-in ethanol, industrial enzymes, organics acids, single cell proteins, and so forth. However, a significant fraction of this biomass goes to industries for steam and electricity generation. The remaining fraction represents the ideal feedstock for the generation high-value commodities.

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