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Composition of sugar cane, energy cane, and sweet sorghum suitable for ethanol production at Louisiana sugar mills

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Abstract A challenge facing the biofuel industry is to develop an economically viable and sustainable biorefinery. The existing potential biorefineries in Louisiana, raw sugar mills, operate only 3 months of the year. For year-round operation, they must adopt other feedstocks, besides sugar cane, as supplemental feedstocks. Energy cane and sweet sorghum have different harvest times, but can be processed for bio-ethanol using the same equipment. Juice of energy cane contains 9.8% fermentable sugars and that of sweet sorghum, 11.8%. Chemical composition of sugar cane bagasse was determined to be 42% cellulose, 25% hemicellulose, and 20% lignin, and that of energy cane was 43% cellulose, 24% hemicellulose, and 22% lignin. Sweet sorghum was 45% cellulose, 27% hemicellulose, and 21% lignin. Theoretical ethanol yields would be 3,609 kg per ha from sugar cane, 12,938 kg per ha from energy cane, and 5,804 kg per ha from sweet sorghum.

Keywords Ethanol · Sugar cane bagasse · Energy cane · Sweet sorghum · Louisiana sugar mills

Introduction

The biofuel industry has greatly expanded in the United States over the past decade due to concern about increasing dependence on foreign oil and increasing levels of atmospheric carbon dioxide. A successful biofuel industry should utilize existing infrastructure. Louisiana has a favorable climate for production of a wide variety of energy crops for bio-fuel production, with an average temperature of 19°C, precipitation of 162.6 cm per year, and a long growing period ranging from 230 to 290 days. Fertile organic soil, semi-tropical climate, adequate water, and abundant sunshine led to the oldest and largest commercial sugar cane industry in the US. Sugar cane has been a part of Louisiana's economy since 1795. Sugar mills are in essence biorefineries that produce multiple products from a single crop. Growth of Louisiana's sugar industry depends on its ability to expand its product offerings outside of a government controlled food product, raw sugar, and extension of its processing season. The nation's push toward biofuels could be an opportunity for Louisiana sugar mills. The production of biofuel from sugar cane bagasse, coupled with that from other sugar containing feedstocks, may provide an opportunity to expand the operational season for Louisiana sugar mills as well as to generate ethanol.

Louisiana sugar mill

Louisiana already has biorefineries in the form of raw sugar mills. Raw sugar mills are located close to sugar cane fields because sugar cane deteriorates within 24 h of harvest. Sugar cane is processed to produce raw sugar, molasses and water in a plant that is fueled by bagasse. Bagasse from sugar cane is burned to produce steam, mechanical power to drive the milling equipment and electricity to drive the rotating equipment in the factory during the harvesting season. So, there is no net import of steam or power. Sugar mills are, in effect, biorefineries, producing multiple

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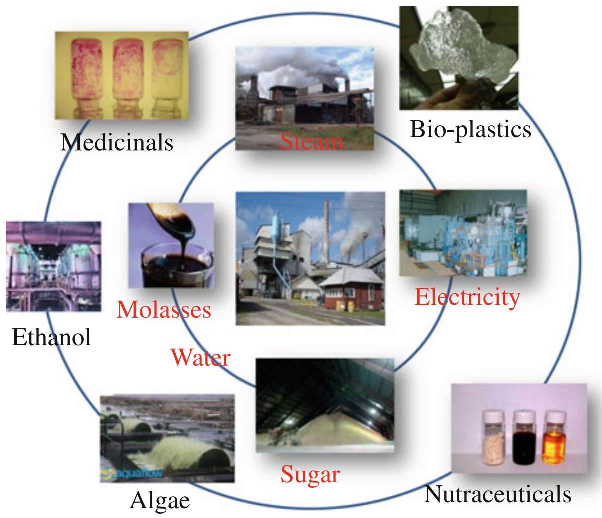

Fig. 1 Louisiana sugar mills as biorefineries

products: raw sugar, molasses, water, steam, and electricity, from a single feedstock (Fig. 1). Existing sugar mills may be able to enhance their bottom line by adding value-added products such as ethanol [1, 2], medicinals [3], bioplastics and neutraceuticals [4]. Co-production of value-added products and fuel enhances the viability of converting conventional sugar mills to fuel biorefineries/sugar mills.

Currently Louisiana sugar mills operate only 3 months of the year, because sugar cane is available only from October to December. Seasonal operation of sugar mills results in low capital utilization, which makes it hard to justify the capital investments to utilize and modernize existing facilities. A reliable and consistent year-round supply of biomass would be required to develop a biomass-based fuel industry. Our approach is to overcome the short processing period by utilizing two additional feedstocks that can be produced on fallow or marginal land. Our selected feedstocks are energy cane and sweet sorghum, both which harvest outside the commercial sugar cane processing season. They are similar in gross composition and shape and can be handled by the traditional sugar cane harvest, delivery, and processing system.

Sugar cane bagasse as a feedstock for ethanol production

Sugar cane (*Saccharum officinarum)* is a tropical perennial grass which is harvested for its sucrose content. It is harvested and processed between October and December every year in Louisiana. In 2009, Louisiana sugar cane was grown on 169,159 ha, and produced 13 million tonnes of raw sugar. Estimated sugar cane production costs, including harvest, ranged from $33 to $39 per tonne and the average price of sugar cane per ha basis from 2000 to 2007 was $63.4 in Louisiana, roughly $3 less than the national average [5]. In the US, it is mostly grown for the production of sugar, whereas Brazil produces ethanol as well as sugar. Significant amounts of sugar cane bagasse remain after juice is pressed from stalks. The amount of bagasse available from 1 tonne of sugar cane ranges between 25 and 300 kg [6]. In general, bagasse is burned to produce steam and electricity as part of a co-generation scheme for the sugar mills. The residual bagasse is stockpiled as an industrial waste with low economic value. In Louisiana, 317,450–589,550 tonnes of bagasse are available yearly for other uses. Bagasse, collected from three Louisiana sugar mills (Cora Texas, Raceland, Enterprise) during sugar season in 2008, contained an average of 41.6% cellulose, 25.1% hemicellulose, and 20.3% lignin (Table 1). Bagasse also offers many advantages for use in the bioconversion processes using microorganisms due to its relatively low ash content (4.8%, Table 1) compared to other feedstocks such as rice straw (17.5%), wheat straw (11.0%), and paddy straw (16%) [7, 8]. We evaluated bagasse for ethanol production, even though leaves and tops are also potential sources of lignocellulosic materials and fermentable sugars. However, in most cases, processors discourage the delivery to the mills of cane stalk with leaves and tops [6]. In Louisiana, materials left in the field are used to keep the temperature of the soil down, delaying germination of the next ratoon and reducing cane yields [9].

Energy cane as a feedstock for ethanol production

Energy cane is a hybrid of commercial and wild sugar canes. It was bred for high fiber content and low sucrose. Average energy cane tonnage is much higher, but brix levels are lower, compared with commercial sugar cane (Table 2). It can withstand the freezing weather in Louisiana during winter and can be available from January to March. The crop cycle of energy cane is a little longer than sugar cane (Table 2). Table 2 also shows that fiber content is approximately double for energy cane when compared to sugar cane. Leal [10] raised concerns about the differences between sugar cane and energy cane in processing of energy cane, such as sugar extraction (water consumption, energy requirements and extraction efficiency) and steam consumption.

Energy cane contains 53.6% juice (wet basis) and 26.7% fiber (dry basis) (Table 1). Approximately 9.8% of sugars were present in juice, and most sugar was sucrose (9.6%). The fiber consists of 43.3% cellulose, 23.8% hemicellulose, and 21.7% lignin.

Table 1 Composition of juice and fiber from each feedstock

	Bagasse[b]	Energy cane[c]	Sweet sorghum[d]
Juice[a] (% total)		53.6	71.9
Sucrose (% juice)		9.6	7.6
Glucose (% juice)		0.1	2.6
Fructose (% juice)		0.1	1.6
Total sugars (% juice)		9.8	11.8
Fiber (% dry weight)		26.7	13.0
Cellulose (% dry weight)	41.6	43.3	44.6
Hemicellulose (% dry weight)	25.1	23.8	27.1
Lignin (% dry weight)	20.3	21.7	20.7
Ash	4.8	0.8	0.4

[a] One kg of stalk was crushed at 2,500 psi for 1 min in a press to extract juice

[b] Bagasse was collected from three Louisiana sugar mills (Cora Texas, Raceland, Enterprise) during sugar season in 2008. Data are averages of 6 runs

[c] Energy cane [L 79-1001(L)] was collected from a farm in the Lake Charles, LA in 2009. Data are averages of 9 runs

[d] Four sweet sorghum (Dale, M81-E, Theis, and Topper) samples were collected from Southeast Research Station at LSU AgCenter in Franklinton, LA in 2009. Data are averages of 17 samples

Table 2 Typical features of feedstocks

Properties	Sugar cane	Energy cane	Sweet sorghum
Crop cycle (months)[a]	10–12	10–15	3.5
Number of cycle/year[a]	One	One	Two
Yield (t/ha/year)[a]	70	100	60
Brix (% juice)[b]	13–15	10–12	11–13
Fiber (% cane)[b]	13.5	26.7	13
Fertilizer requirement (N:P:K)[a]	300:150:150	300:150:150	100:50:50

[a] Data were collected from Louisiana State University Agricultural Center and personal communication with Dr. Benjamin L. Legendre, Professor and Agronomist at Audubon Sugar Institute, LSU AgCenter

[b] The measurements for brix and fiber were conducted at Audubon Sugar Institute

Based on estimates of cellulosic ethanol production costs by Mark et al. [11], ethanol would cost about 69 cents per liter using energy cane, at an average yield of 67 tonne per ha, whereas it would be about 51 cents per liter for corn using conventional fermentation technology with a corn price of $4 per bushel.

Sweet sorghum as a feedstock for ethanol production

Sweet sorghum (*Sorghum bicolor* L. Moench) can be adapted to almost all temperate and tropical climates as an annual or short perennial crop. It has potential to be drought resistant, as it remains dormant during the driest period [12]. It requires less fertilizer and water than other sugar crops such as sugar cane and energy cane [13]. Sweet sorghum in Louisiana could be easily incorporated into an existing sugar cane infrastructure, as sugar cane farmers could use the same harvest and transportation equipment [14]. It can be planted on the fallow sugar cane lands during the spring season as it follows the plowing out of the previous sugar cane stubble crop and preparation of the seed bed [14, 15]. Viator et al. [14] estimated the production costs of sweet sorghum to be $477 per ha which includes plowing out the previous sugar cane stubble, planting sweet sorghum, expenses for seed, fertilizer, herbicides, fuel and labor, and the harvest costs to be $358 per ha (around $13 per tonne).

Sweet sorghum has a 3.5 month crop cycle and can be cultivated twice a year. Sweet sorghum has lower feedstock yield, brix levels, and fibers than sugar cane. Fertilizer requirements for growing sweet sorghum are a third those of sugar cane (Table 2).

As do sugar cane and energy cane, sweet sorghum also contains juice and fiber. Juice contains 11.8% of sugars, consisting of sucrose, glucose, and fructose which can be readily converted to ethanol (Table 1). Sweet sorghum

Table 3 Theoretical ethanol production from one tonne of multiple feedstocks (kg, dry basis)

Component	Sugar cane	Energy cane	Sweet sorghum
Feedstock	1,000	1,000	1,000
Juice[a]	0	536	719
Fiber	135	267	130
Sugar			
Monomeric sugar from juice	0	53	85
Glucose from cellulose[b]	62	128	64
Xylose from hemicellulose[c]	39	72	40
Ethanol			
Ethanol from juice[d]	0	27	43
Ethanol from cellulose[d]	32	66	33
Ethanol from hemicellulose[d]	20	37	20
Total ethanol	52	129	97

[a] Juice is wet kilograms

[b] Glucose (kg) = Glucan (kg) × 1.11; 1.11 is a conversion factor considering water addition during hydrolysis

[c] Xylose (kg) = Xylan (kg) × 1.14; 1.14 is a conversion factor considering water addition during hydrolysis

[d] Ethanol (kg) = Glucose, fructose, sucrose, or Xylose (kg) × 0.511; 0.511 is a conversion factor for sugar to ethanol based on stoichiometric biochemistry of yeast

Table 4 Theoretical ethanol production from multiple feedstocks (kg/ha, dry basis)

Component	Sugar cane	Energy cane	Sweet sorghum
Feedstock	70,000	100,000	60,000
Juice[a]	0	53,600	43,140
Fiber	9,450	26,700	7,800
Sugar			
Monomeric sugar from juice	0	5,253	5,091
Glucose from cellulose[b]	4,368	12,846	3,865
Xylose from hemicellulose[c]	2,695	7,221	2,402
Ethanol			
Ethanol from juice[d]	0	2,684	2,601
Ethanol from cellulose[d]	2,232	6,564	1,975
Ethanol from hemicellulose[d]	1,377	3,690	1,227
Total ethanol	3,609	12,938	5,804

[a] Juice is wet kilograms

[b] Glucose (kg) = Glucan (kg) × 1.11; 1.11 is a conversion factor considering water addition during hydrolysis

[c] Xylose (kg) = Xylan (kg) × 1.14; 1.14 is a conversion factor considering water addition during hydrolysis

[d] Ethanol (kg) = Glucose, fructose, sucrose, or Xylose (kg) × 0.511; 0.511 is a conversion factor for sugar to ethanol based on stoichiometric biochemistry of yeast

juice is not used for the production of refined sugar because of unfavorable sucrose to reducing sugar ratios [16, 17].

Comparison of ethanol yields for multiple feedstocks

Our selected multiple feedstocks contain two materials which can be converted to ethanol—(1) simple sugars from juice and (2) lignocelluloses from fiber. Juice contains sucrose, glucose, and fructose which can be directly fermented by *Saccharomyces cerevisiae* after extraction. Ethanol production from lignocellulosic biomass through the biochemical route requires three major steps: pretreatment, enzymatic hydrolysis, and fermentation.

Theoretical ethanol production from one tonne of each feedstock is given in Table 3. It was assumed that all available cellulose and hemicellulose found in Table 1 are converted into monomeric sugars, all monomeric sugars also are completely fermented by *S. cerevisiae* to produce ethanol; there is no loss throughout the entire process.

Sweet sorghum produces more ethanol from juice than energy cane. Ethanol produced from cellulose is approximately double for energy cane when compared to sugar cane and sweet sorghum. Wild type *S. cerevisiae* can ferment only glucose from lignocellulosic biomass. To produce ethanol from hemicellulose, a genetically modified *S. cerevisiae* which is able to ferment pentoses would be required. Lignocellulosic material from sweet sorghum could produce the same quantities of ethanol as that from sugar cane. Ethanol production from energy cane (129 kg) could be higher than from other feedstocks (52 kg ethanol from one tonne of sugar cane versus 97 kg from sweet sorghum).

Table 4 summarizes the theoretical ethanol yields using multiple feedstocks produced from 1 ha of land. The assumption is that each feedstock is cultivated and harvested once a year. It is possible that 12,938 kg per ha of ethanol can be produced from energy cane, 5,804 kg per ha from sweet sorghum, and 3,609 kg per ha from sugar cane bagasse under the ideal conditions for each feedstock. The theoretical ethanol yields using multiple feedstocks are superior to those using maize [18]. Schwietzke et al. [18] compared the theoretical ethanol yields for conversion of starch, by-products, and corn stover from maize. The highest ethanol production (6,805 kg per ha) could be attained when all three components such as starch, by-products, and corn stover from maize were used [18]. The theoretical yield of corn grain was 4,023 kg per ha [18].

Conclusions

A consistent and reliable year-round supply of feedstocks is a significant cost component for bio-ethanol production. This study showed that both energy cane and sweet sorghum, which have harvest times different from sugar cane, were similar in gross structure and chemical composition. They could be handled by a traditional sugar cane harvest and processing system. Utilization of energy cane and sweet sorghum outside the sugar cane season in Louisiana has the possibility to increase ethanol production as well as to expand the feedstock supply. Although this study establishes a base case for the use of these crops for the production of bio-ethanol, there are still many challenges. These include determining the optimum conditions for milling, pretreatment, and enzymatic hydrolysis of each feedstock to maximize ethanol yields, feasibility of incorporating new crops into the existing sugar cane infrastructure, and possibility of partitioning feedstocks for both fuel and sugar during normal sugar cane processing season in Louisiana.

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