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Model study on extraction of fermentable sugars and nonstructural carbohydrate from sweet sorghum using diffusion process

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ABSTRACT

Sweet sorghum stores a high concentration of soluble sugars in its stalk and produces grain in the panicle. This grain represents a significant amount of starch. The ethanol industry currently uses sugarcane processing methods for sweet sorghum; however, sweet sorghum differs from sugarcane in that sweet sorghum produces significant quantities of grain which is predominantly starch. The objective of this research was to increase ethanol production from sweet sorghum by fully utilizing all fermentable sugars which include starch in the grain and nonstructural carbohydrates in the stalk. The diffusion process was utilized to extract fermentable sugars and nonstructural carbohydrates from chopped sweet sorghum biomass and grains. Response surface methodology (RSM) was applied in order to optimize diffusion conditions and to explore effects of diffusion time, diffusion temperature, ratio of sweet sorghum grain to total biomass on starch-to-sugar efficiency, and total sugar recovery from sweet sorghum. RSM results showed that starch conversion efficiency and sugar recovery efficiency of 96% and 98.5%, respectively, were achieved at an optimized time of 114.9 min, temperature of 95 °C, and 22% grain loading.

1. Introduction

Sweet sorghum (*Sorghum bicolor* (L.) Moench), a C_4 plant, is a unique and versatile sugar crop that can be separated into starchy grains, soluble sugar in juice extracted from the stalk, and lignocellulose biomass (Rao et al., 2013; Blummel et al., 2009). All these components can be processed into ethanol (starch-based and cellulosic), syrup, animal feed, and electricity, as well as used as substrate for hydrogen and methane production (Antonopoulou et al., 2008; Gnansounou et al., 2005; Li et al., 2013). The juice extracted from sweet sorghum stalks contains water-soluble nonstructural carbohydrates (sucrose, glucose, and fructose) and structural carbohydrates (cellulose and hemicellulose) (Li et al., 2013; Serna-Saldívar et al., 2012a). The juice from the stalk may contain 20 to 50% of dry matter of the entire plant (Whitfield et al., 2012). Using modelling, Rainey and O'Hara (2013) reported that a total ethanol yield of 8130 L/ha could be achieved from sweet sorghum, assuming a total productivity of 60 t/ha of sweet sorghum consisting of 3 t/ha of grain (73% starch), 50 t/ha of stalk (15% total sugars and 15% dry fiber), and 7 t/ha of leaves (40% dry fiber). The grain yield is typically 3–7 t/ha (Rainey and O'Hara, 2013; Rao et al., 2013), and stalk yield per hector is 45–65 ton (Rao et al., 2013). Recent studies have shown that sweet sorghum juice could be incorporated into the current starch-based ethanol process in order to conserve water and achieve yields of 28% higher than the conventional process (Appiah-Nkansah et al., 2015). Ethanol fermentation efficiencies of sweet sorghum from juice could range from 85 to 93% (Appiah-Nkansah et al., 2015; Serna-Saldívaret al., 2012b).

Fermentable sugar composition of sweet sorghum feedstock range from 16 to 22% as compared to sugarcane juice (12–17.6%), sugar beet juice (16%), and watermelon juice (7–10%) (Zabed et al., 2014). In addition, sugar yields from sweet sorghum have been reported to be 4–10 t/ha as compared to sugarcane (5–12 t/ha) and sugar beet (11.25–18 t/ha) (Rao et al., 2013; Regassa and Wartmann, 2014). Sweet sorghum grain, which consists of 60–70% starch, can be hydrolyzed and saccharified into glucose and subsequently fermented to produce biofuels (O'Hara, 2013; Albertson et al., 2013; Rainey and O'Hara, 2013). Based on these numbers, sweet sorghum is a competitive bioethanol feedstock that could be integrated into existing sugarcane ethanol-processing plants. However, only three sugarcane plants are known to incorporate sweet sorghum crop into their facilities—Mossman Central Factory in Australia, the

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Table 1
Experimental design with RSM.

Run	Coded variables			Actual experimental variables			Starch efficiency, [b]Y_{SE} (%)	Sugar recovery efficiency, [c]Y_{SRE} (%)
	Time (X_1)	Temp (X_2)	Grain (X_2)	Time (min) (X_1)	Temp °C (X_2)	[a]Grain (%) (X_3)		
1	−1	0	−1	60	85	15	77.85	94.46
2	+1	0	−1	120	85	15	84.36	96.09
3	−1	0	+1	60	85	25	78.74	91.78
4	+1	0	+1	120	85	25	87.88	95.31
5	−1	−1	0	60	75	20	71.65	90.90
6	+1	−1	0	120	75	20	78.12	92.98
7	−1	+1	0	60	95	20	87.04	95.84
8	+1	+1	0	120	95	20	95.23	98.47
9	0	−1	−1	90	75	15	72.57	93.14
10	0	−1	+1	90	75	25	76.32	90.85
11	0	+1	−1	90	95	15	89.81	97.45
12	0	+1	+1	90	95	25	94.82	98.00
13	0	0	0	90	85	20	84.37	94.98
14	0	0	0	90	85	20	86.67	95.72
15	0	0	0	90	85	20	85.97	95.50

[a] Grain (%) is percentage of grain loading.
[b] Y_{SE} is the starch conversion efficiency.
[c] Y_{SRE} is the sugar recovery efficiency.

Triangular Sugar Mills in Zimbabwe, and U.S. Department of Agriculture pilot plant in Texas (Rainey and O'Hara, 2013; Smith et al., 1973; Woods, 2000).

Sweet sorghum has a similar physiological structure to sugarcane, thereby allowing use of the same mechanical harvesting approach. Sweet sorghum can also be manually harvested and the stalk can be expressed in the field. In the manual harvesting process, the crop is topped and the leaves are stripped before crushing the stalk for juice extraction (Regassa and Wartmann, 2014). The topped panicle is composed of grain that is left in the field. Consequently, a significant amount of starch (60–70%) that could be hydrolyzed is left in the field.

Traditionally, juice extraction is achieved by pressing the stalk of the crop through a roller mill, but this process is slow, labor intensive, and less efficient, with juice recovery below 50% (Regassa and Wortmann, 2014; Whitfield et al., 2012). Low juice extraction yield could be attributed to the relatively high fiber content of sweet sorghum stalk compared to sugarcane (Gnansounou et al., 2005). Another drawback associated with the milling process is sugar loss due to microbial activities (Wu et al., 2010; Whitfield, 2012). Wu et al. (2010) reported that up to 50% of total fermentable sugars in sweet sorghum is lost if the expressed juice is stored for one week at room temperature. This loss is a result of microorganisms that metabolize the sugars at room temperature (≈25 °C), under the low pH (≈4.7) and anaerobic into organic acids (lactic acid, formic acid, acetic acid), carbon dioxide, and ethanol.

Diffusion is an alternative to juice extraction from the stalk. In this process, biomass is hammer-milled to uniform particle sizes and then passed through a series of continuous hot water flushes in which the concentration of solute is continuously reduced (Rein, 1995). Thus, liquid extraction recovers the sugars from cane tissues, while the conventional milling process employs mechanical juice expression. The diffusion method is the more effective of the two methods because it can achieve very high sucrose extraction (pol/sucrose ration of 0.988) (Rein, 1995). The diffusion system is also energy efficient and requires lower maintenance and capital costs because of lack of excessive pressure and shear forces of the roller mills (Cotlear, 2004). Typically diffusion plants include dewatering mills which utilizes approximately half of the power required in energy-intensive hammer mill (Rein, 2007).

The objective of this research was to enhance the economic attractiveness of ethanol production from sweet sorghum using technological developments in order to fully utilize fermentable sugars, starch in the panicle, and nonstructural carbohydrates in the stalk for high efficiency and low-cost ethanol production. In this work, response surface methodology (RSM) was applied in order to study the interactive effect of diffusion time, diffusion temperature, and grain loading on sugar extraction from sweet sorghum feedstock.

2. Material and methods

2.1. Materials

Sweet sorghum grain and dried bagasse were obtained from Texas A&M University, College Station, Texas, for this research. The sweet sorghum was harvested just after physiological maturity of the grain in the panicle. At this stage of growth the grain is fully developed, has approximately 30% moisture content and stalk sugar content has peaked and will start to reduce with increased maturity. The bagasse was carefully screened to remove grain kernels using a Seedburo seed blower (Seedburo Equipment Co., Des Plaines, IL). The grain and bagasse, separately milled through a 3.99 mm screen in a Schutte Buffalo hummer mill (Schutte-Buffalo Hammermill, LLC, Buffalo, NY), were used for the diffusion test and analysis. Moisture content of the materials was determined as bagasse (4.88%) and grain flour (11.68%) using standard American Association of Cereal Chemists (AACC) and National Renewable Energy Laboratory (NREL) methods (AOAC, 2000; Sluiter et al., 2008.) The bagasse and grain flour were stored in sealed plastic bags at room temperature, and starch content of the sorghum grain was analyzed using a total starch kit (Megazyme International) in adherence to the AACC standard method (AACC, 2000).

2.2. Sugar extraction by starch hydrolyses and diffusion process

To determine starch-to-sugar conversion efficiency and sugar recovery efficiency, initial fermentable sugars in the sweet sorghum bagasse were used as the control. For sugar extraction, 40 g of biomass (grain + bagasse) was weighed in a 500 mL beaker. Approximately 750 mL of distilled water was preheated in a microwave for 5 min, and 500 mL of the preheated water was measured. Approximately 400 mL of the preheated water was poured into the 1 L reaction vessel of a Parr pressure reactor (Parr Instrument Co.,