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Sweet Sorghum as a Bioenergy Crop for the US Great Plains

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1. Introduction

Sorghum (*Sorghum bicolor* L. Moench), including sweet sorghum, is widely adapted to diverse and often marginal crop production environments. Sweet sorghum stalks have high sugar content compared with other sorghum types and has potential for producing ethanol to be mixed with gasoline or for producing ethyl tert-butyl ether, an octane additive to gasoline. Sweet sorghum was introduced to the United States for syrup production in the 1850s (Winberry, 1980). Production peaked following sugar shortages during World War II at about 136 million L yr^{-1} of syrup in 1946 (Hunter & Anderson, 1997), but thereafter declined because of low sugar prices and inadequate production efficiency.

Sweet sorghum can be competitive with corn (*Zea mays* L.) and grain sorghum for ethanol yield when grain yield is less than 9 Mg ha^{-1}, and is comparatively efficient in nitrogen use (Smith & Buxton, 1993). Sweet sorghum can easily substitute for corn or grain sorghum in many cropping systems.

Currently, most ethanol produced in the U.S.A. is from the starch of corn grain with the support of federal subsidies. Energy gains with production of ethanol from grain are modest, typically ranging from 30 to 130% depending on N use efficiency, ethanol plant efficiency, and the efficient use of the distillers grain co-product. Sweet sorghum can be produced at less cost than corn, often with higher energy gains (Smith & Buxton, 1993). Rather than producing starch, sweet sorghum carbohydrates are stored in the stalk as sugar, with sugar concentrations of 8-20% (Rains et al., 1990). Conversion of sugar to ethanol requires less energy than starch as much energy is used to depolymerize the starch. Sweet sorghum has demonstrated potential to produce up to 6000 L ha^{-1} of ethanol in Iowa and Colorado U.S.A. (Smith & Buxton, 1993), equivalent to ethanol from approximately 20 Mg of corn grain. However, estimated ethanol yields were on average 33% more with grain of corn and grain sorghum compared with sugar of sweet sorghum for seven rainfed site-years in Nebraska U.S.A. (Wortmann et al, 2010). Seasonal availability, the need to transport and store much mass, and storability of sweet sorghum constrain sweet sorghum as a bio-energy crop.

In planning for bio-fuel production, long-term sustainability of cropping systems must be considered. Sustainability of a cropping system is very much dependent on production environment and resource availability. In one study comparing the sustainability of different bioenergy crops, sweet sorghum, along with oil palm (*Elaeis guineensis* L.) and sugarcane (*Saccharum* spp.) for biofuel, were found to be more sustainable in comparison to

maize and wheat. This assessment considered efficiency in use of land, water, nitrogen and energy resources, and of pesticides, relative to net energy produced (Vries et al., 2010).
This chapter addresses sweet sorghum production for the U.S. Great Plains and other temperate production zones, harvest and processing issues, and energy and green house gas balances. An extensive literature review was conducted with most published papers reporting on research conducted in temperate zones.

2. Sweet sorghum production

2.1 Growth and sugar content

The agronomic principles and production practices for sweet sorghum and grain sorghum are similar (Hunter & Anderson, 1997). Reddy et al. (2005) reported much diversity among sweet sorghum genotypes with ranges in India of 13 to 24% for Brix (a measure of sugar and soluble starch in plant sap based on light refraction; a typical Brix measure for sweet sorghum sap is 85% sugar and 15% soluble starch), 7.2 to 15.5% for sucrose concentration in juice, 24 to 120 Mg ha^{-1} for fresh stalk yield, 36 to 140 t ha^{-1} fresh biomass yield, and 27 to 48 Mg ha^{-1} mill-ready stalk yield. Plant height can be as tall as 4.8 m (Freeman & Broadhead, 1973) and stalks can be more than 45 mm thick (Turhollow, 1994). Sweet sorghum has a range of maturity types, and is relatively well adapted compared with corn to water deficit stress, but yields are typically highest in deep, well-drained soils with good fertility. Sweet sorghum has the potential for producing a ratoon crop after harvest where the growing season is long enough.
Sweet sorghum growing degree days and thermal time are commonly calculated with a base temperature of 13^{o} C (Barbanti et al., 2006; Ferraris & Charles-Edwards, 1986). Sugar yield is generally favored by early planting, but rapid emergence and vigorous seedling growth occur when soil temperature is above 18^{o} C at planting (Lueschen et al., 1991). Sugar yield was increased with earlier planting and increased radiation during the reproductive stage (Ferraris & Charles-Edwards, 1986). Ricaud & Arenneaux (1990) reported mean stalk yields of 56 and 49 Mg ha^{-1} with 26 Apr and 25 May planting, respectively, in Louisiana U.S.A. Yield of stalk sugar in excess of 10 Mg ha^{-1} was observed for early sown crops and the sugar yield dropped to 3 Mg ha^{-1} for late-planted crops (Ferraris & Charles-Edwards, 1986). Juice yield was not affected by planting date in Mississippi U.S.A., but sugar yield was highest for early May planting (Broadhead, 1972) and similar for April and June planting (Broadhead, 1969). In another study conducted in the upper Midwest of the U.S.A., fermentable carbohydrate and ethanol yields were 13% more with earlier compared with later planting dates, and early planting of late-maturing sweet sorghum cultivars was recommended, despite a problem of lodging.
Sugar concentration of sweet sorghum increased as a function of the duration of growth, commonly peaking at the grain dough stage, and generally decreased with delayed planting irrespective of sampling stage (Ferraris, 1981; Geng et al., 1989). Planting of full season varieties commonly increases potential ethanol yield (Putnam et al., 1991; Zhao et al, 2009). The rate of sugar accumulation is nearly linear with growing time and with radiation intercepted. Early planting allows for a longer growing period and earlier canopy development for sunlight interception during the long days of June and July. The same studies found that production of highly-recoverable concentrated sugars was maximized with long season, tall- and thick-stalk sweet sorghum cultivars. Interception of radiation during the boot to early seed formation growth stage has been found to be very important to sweet sorghum sugar yield (Hipp et al., 1970).

2.2 Plant population and stand establishment

Uniform seedling emergence and vigorous stand establishment is important for sweet sorghum production but often challenging under unfavorable planting conditions. This is due to small seed size and often low germination rate and seedling vigor compared to grain sorghum. Once the crop has reached the fifth leaf stage, sweet sorghum growth is generally vigorous and competitive.

Several studies have addressed plant population and planting pattern. Across seven rainfed site-years in Nebraska, Wortmann et al. (2010) found similar harvestable stem number and sugar yield by sowing 7.5, 12.5, and 17.5 seed m^{-2} with 75-cm row spacing; increased harvestable tiller number compensated for the lower sowing rates. Sweet sorghum stalk yield was greater in Turkey with 15 plants m^{-2} compared with lower plant densities when planted with 65-cm row spacing (Turgut et al., 2005). In the northern Corn Belt of the U.S.A., sweet sorghum fermentable carbohydrate or ethanol yield was not affected by seeding rate (Lueschen et al., 1991). In a study of carbohydrate accumulation conducted in Australia, Ferraris & Charles-Edwards (1986) found lower early sugar concentration but slightly higher concentration with higher plant density. Broadhead and Freeman (1980) and Kuepper (1992), however, found reduced Brix, sucrose content, sugar yield, and juice content with increased plant density (Broadhead & Freeman, 1980; Kuepper, 1992).

Row spacing may be important. In Australia, Martin and Kelleher (1984) reported increased stalk and water soluble carbohydrate yield with 8 compared with 16 plants m^{-2} and when row spacing was reduced from 105 to 35 cm. They attributed the row spacing effect to greater photosynthetic productivity before anthesis and the production of taller, thicker stalks, the volume of which was closely related to post-anthesis carbohydrate accumulation. In Mississippi U.S.A., stalk yield and Brix were more by growing sweet sorghum in 52.5 cm row spacing compared with wider row spacing, but individual plant weight and juice content were more in wider rows and lodging was less (Broadhead & Freeman, 1980). In this study, however, stalk and sugar yield per hectare with 76-cm row spacing was similar compared with narrower row spacing and more than with 105-cm spacing.

2.3 Water use

Sweet sorghum has been observed to extract soil water to 270 cm depth in California U.S.A. (Geng et al., 1989). In this study, sweet sorghum had less yield loss compared to corn, sugarbeet (*Beta vulgaris* L.), and fodder beet (*Beta vulgaris* L.) under severe soil water deficit conditions. Water use efficiency of sweet sorghum was determined to be 310 compared to 370 kg water kg^{-1} dry matter for corn (Reddy et al., 2007). With adequate nutrient supply and irrigation, sweet sorghum hexose yield was 10.0 Mg ha^{-1} compared to 8.1 Mg ha^{-1} for corn (Geng et al., 1989), while under soil water deficit conditions sweet sorghum extracted more soil water and produced 29% more hexose compared with corn. In trials conducted between 40.8° and 42.0°N latitude in the U.S.A., total sugar and ethanol yield were similar, but total biomass yield was more with irrigated compared with rainfed production. Seasonal rainfall was not related to biomass or sugar yield in Nebraska U.S.A. where the cropping season rainfall ranged from 250 to 580 mm; median water productivity was 50 kg biomass and 8.1 kg of sugar per mm of seasonal rainfall (Wortmann et al., 2010); this did not account for stored soil water at one month before planting and available soil water remaining after harvest.

Most sweet sorghum research has been conducted under rainfed conditions. However, a study in Arizona U.S.A. on a sandy soil evaluated frequency of irrigation (Ottman & Miller, 2010). They found sweet sorghum to be responsive to irrigation under arid conditions but did not appear to be highly sensitive to frequency of irrigation. Water use was less and water use efficiency was greater when irrigating at 50 and 65% depletion of available soil water compared with irrigating at 35% depletion (Miller & Ottman, 2010).

2.4 Fertilizer use

Sweet sorghum response to applied nutrients varies with location. Dry plant yield in Louisiana U.S.A. was 40% more with 100 kg ha^{-1} N compared to no N applied; yield was not further increased with application of an additional 100 kg ha^{-1} N, but there was a 10% yield increase with addition of 90 kg ha^{-1} K (Ricaud & Arenneaux, 1990). They reported a 50% increase in total sugar yield by applying 100 kg ha^{-1} N, an additional 4% increase by increasing the N rate to 200 kg ha^{-1} N, and an additional 13% gain by adding 80 kg ha^{-1} K to the 100 kg ha^{-1} N. Nutrient uptake by sweet sorghum at the soft dough stage ranged from 109 to 214 with a median of 142 kg ha^{-1} for N, 11 to 31 with a median of 18 kg ha^{-1} for P, and 60 to 161 with a median of 113 kg ha^{-1} for K (Ricaud & Cochran, 1979). In a comparison with other potential bioenergy crops conducted in Kansas U.S.A., N and K removal in the above ground biomass was more with sweet sorghum compared with other crops, and P removal was less compared with maize and perennial grasses (Table 1) (Propheter & Staggenborg, 2010).

Sweet sorghum biomass yield in Turkey was increased by 16% and stalk diameter by 7% with application of 100 kg ha^{-1} N (Turgut et al., 2005). In California U.S.A., sweet sorghum used applied N much more efficiently than corn. Sweet sorghum required just 36% of the fertilizer N required by corn to maximize hexose yield, but produced 23% more hexose yield than corn (Geng et al., 1989). In Mississippi U.S.A., stalk yield was 24% more with the application of 45 kg ha^{-1} N compared to no N applied, but similar to the yield with application of 90 kg ha^{-1} N or with P application (Freeman & Broadhead, 1973). In other studies, fermentable sugar yield (Smith & Buxton, 1993), stalk dry matter yield at harvest (Barbanti et al., 2006), and fermentable carbohydrate and ethanol yield (Lueschen et al., 1991) were not affected by N application. In Texas U.S.A., total dissolved solids in juice decreased when a high N rate was applied (Wiendenfeld, 1984). Sweet sorghum did not respond to applied N when intercropped with alfalfa (Buxton et al., 1998). However, farmers producing sweet sorghum for syrup generally applied 34 to 56 kg ha^{-1} of fertilizer N (Kuepper, 1992). Some sweet sorghum cultivars have the capacity for associative N fixation with 0 to 18% of plant N determined, using the ^{15}N natural abundance technique, to be derived from the atmosphere (Yoneyama et al., 1998).

Sweet sorghum stalk dry matter and sugar yield were increased with application of 80 kg ha^{-1} N at only one of seven site-years in Nebraska U.S.A. while corn and grain sorghum grain yields were increased for all site-years with N application (Wortmann et al., 2010). Unpublished results from a related study in Nebraska U.S.A. found that total N uptake by sweet sorghum was similar to uptake by corn but the pattern of uptake differed. Nitrogen uptake by sweet sorghum was more gradual over a longer period of time than for corn and grain sorghum that had several weeks with a very high rate of uptake. Therefore, the high soil N supply needed by the grain crops compared with sweet sorghum at those critical growth stages likely accounted for the greater responsiveness of the grain crops to applied N. Sweet sorghum continued to take up N later into the season, allowing more time for soil organic N mineralization and for deeper root penetration and uptake of deep nitrate-N.

	Nutrient removal, kg ha^{-1}		
	N	P	K
Sweet sorghum	190	34	329
Maize	174	43	167
Forage sorghum†	152	34	292
Perennial grass†	43	48	52

†The forage sorghum values are means of three varieties including a photoperiod-sensitive sorghum. The perennial grass values are means of three species, including switchgrass (*Panicum virgatum* L.), big bluestem (*Andropogon gerardii* L.), and miscanthus (*Miscanthus giganteus*).

Table 1. Mean nutrient removal with the harvest of the above-ground biomass of four groups of bioenergy crops at two locations in Kansas U.S.A. (Propheter & Staggenborg, 2010).

Sweet sorghum biomass and juice yield increased with lime application when soil pH was low (Soileau & Bradford, 1985). Surface soil organic matter was 10 g kg^{-1} soil in this study and yields were depressed with N application in the absence of lime application.

3. Harvest, juice extraction, and transport

3.1 Sweet sorghum stalk harvest

Sweet sorghum stalk yield was not much affected by growth stage between flowering to physiological maturity but juice extraction efficiency decreased, and Brix and starch increased, with advancing maturity (Broadhead, 1974); sucrose yield was maximized during the dough stage. In other studies, syrup yield was maximized by harvesting during the late milk to hard dough growth stage (Broadhead, 1972; Tarpley et al., 1994). Stalk sugar concentration is often the lowest at boot stage and the highest at the soft dough stage (Lingle, 1987; Ricaud et al., 1979); the onset of sucrose accumulation was associated with the onset of the reproductive phase of growth and reduced acid invertase activity. Juice yield, per cent extracted, and purity were not affected by delaying stalk harvest until 3-4 weeks after physiological maturity, but Brix and sucrose were reduced by 6% and 4%, respectively, compared with harvest at or before physiological maturity (Broadhead, 1969). Sugar concentration of juice increased continuously until frost kill but thereafter declined (Nuese & Hunt, 1983). Sugar yield is dependent on length of growing season and the amount of radiation intercepted, with a linear increase in sugar yield at dough stage as photosynthetically active radiation increased from 20 to 80 MJ plant^{-1} due to earlier sowing and longer growing periods (Ferraris & Charles-Edwards, 1986). As long as the terminal meristem developed, the internodes increased in biomass and plant height increased, especially in late maturing cultivars (Coleman & Belcher, 1952). Sugar continued to accumulate in the fully-developed internodes well into seed development (Hunter & Anderson, 1997). In balancing potential ethanol yield with extending the harvest period, harvest of early maturing varieties may begin at about 20 days after anthesis (Zhao et al., 2009).

In traditional harvest for syrup production, sweet sorghum stalks were topped to remove the panicle and stripped of leaves before crushing for juice extraction because of effects on syrup taste (Winberry, 1980). Farmers staggered plantings over four weeks to prolong the harvest period (Broadhead, 1974). Juice was extracted with simple wooden or metal roller presses, a labor intensive procedure (Lamb, 1982). Juice extraction could be done without stripping stalks of leaves without syrup yield loss if: 1) the leaves were wilted before juice extraction; 2) juice was decanted after at least two hours of settling to remove sediment; and 3) alpha-amylase enzymes were used during preheating of the juice (Kuepper, 1992). Panicle and leaf removal is less important for ethanol production since taste is not an issue as it is for syrup produced for human consumption.

De-heading of sweet sorghum at anthesis resulted in more productive tillers and increases in main stalk diameter by 20%, juice yield by 30%, and sugar yields by 10% in India, but 5% less Brix, sucrose concentration, and juice purity (Rajendran et al., 2000). In another study, de-heading increased Brix and concentrations of sucrose and starch at the milk through physiological maturity growth stages while reducing plant lodging and increasing tillering, resulting in increased juice yield (Broadhead, 1973). Stalk water content was less with deheading but this did not reduce sugar yield (Broadhead, 1973; Hunter & Anderson, 1997).

Sweet sorghum produces much biomass and handling this biomass in the short harvest windows available in temperate zones poses a major challenge (Bennett & Anex, 2008). Modified forage harvesters that cut stalks into billets may be used for chopping and harvesting stalks before transporting to the juice expression site, but sugar loss before juice extraction is slower with intact compared to chopped stalks (Bennett & Anex, 2008).

In-field extraction of juice reduces the biomass to be transported, leaving the bagasse in the field for ground cover and nutrient cycling. A field harvester capable of expressing juice into large bladders for juice storage and fermentation has been proposed, but sugar extraction may be 30-40% less with current in-field extraction technology compared with larger stationary extraction equipment (Kundiyana et al., 2006).

Parameter†	**Value**
Sugar-to-ethanol yield	%
Stalk juice extraction	80
Brix to fermentable sugar	75
Fermentable sugar converted to alcohol	95
Grain and sugar conversion to ethanol	**L Mg^{-1}**
Maize or grain sorghum grain	423
Sweet sorghum sugar	665
Crop production and harvest, diesel-equivalent	**L ha^{-1}**
No-till production	4
Grain harvest, > 8 Mg ha^{-1} yield, L ha^{-1}	13
Sweet sorghum harvest and extraction, L M^{-1} of fresh stalks	0.3
Natural gas consumed to produce ethanol	**MJ L^{-1}**
Grain	5.44
Sugar	3.33

†Adapted from Wortmann et al., 2010. Other values used in calculations are reported in the BESS2008.3.1 User's Guide (www.bess.unl.edu; verified Mar. 24, 2011).

Table 2. Values used in calculations of ethanol yields and energy balance of maize, grain sorghum, and sweet sorghum with only the grain or sugar used for ethanol production in Nebraska U.S.A.

A self-propelled 4-row forage harvester adapted for sweet sorghum harvest was found to be economically competitive with other harvest alternatives; when the co-product value was included, the net farm-gate cost of fermentable carbohydrates ranged from \$7 to \$24 Mg^{-1} and less than the cost of fermentable carbohydrate of corn grain (Bennett & Anex, 2008). Mobile juice-extracting alternatives were not found to be economically competitive with stationary units, assuming reduced quality control and juice extraction efficiency. If the harvest area is near the juice extraction facility, the lower fermentable carbohydrate costs of sweet sorghum compared with corn grain were sufficient to offset increased costs of transporting the wet sweet sorghum biomass. However, processing costs were reduced by 50% with a processing plant of 379,000,000 L yr^{-1} compared to a small plant of 37,900,000 L yr^{-1} but requiring longer transport distances plus much storage capacity and much added cost (Bennett & Anex, 2009). Ensiled storage of wet sorghum stalks resulted in 20% loss of fermentable carbohydrates plus added costs, with the result that ethanol production from sweet sorghum was more costly than for maize grain. However, ethanol production from fresh sweet sorghum feedstock, even with the high transport costs, was more cost effective compared with grain of maize. In many studies, sugar yield is estimated based on Brix readings and expected efficiency of juice extraction. The relationship of Brix to sugar content and efficiency of juice extraction vary with the actual values dependent on numerous factors. It is important that the conversion factors be reported such as those reported in Table 2 in order that the results can be adjusted for the reader's conditions.

3.2 Stalk storage and juiced extraction

Delays in extracting juice with a stationary press following harvest of stalks often occur. Sugar loss from heaped intact stalks was just 3% in four days (Ricaud et al., 1979) and no significant sucrose inversion occurred during 24 hours after cutting. In another study, juice extraction and purity decreased by 3% and 5%, respectively, during 24 hours following intact stalk harvest, but sucrose and starch decreased by less than 1% during 48 hours after harvest (Broadhead, 1974). Temperature during storage appears to be important to losses with 20% of fermentable sugars lost in 3 days of storage at room temperature but no loss with refrigeration (Wu et al., 2010).

Chopped stalks can be stored as silage without appreciable sugar loss in fermentation if inhibited with an acrylic acid treatment (Hill et al., 1987), but a 20% loss in ensiled storage can occur without such treatment (Bennett & Anex, 2008).

There is evidence of an interaction of harvest growth stage and stalk storage time (Broadhead, 1974). Juice purity was not affected by harvest growth stage if the stalks were not stored, but juice purity was 70 and 73% less at 24 hours of storage for stalks harvested in the milk compared with the dough and physiological maturity stages, respectively.

Juice extraction efficiency can be improved by removing panicles and leaves (Lamb, 1982). Expression efficiency may be improved by repeated re-watering and re-expression and by maceration of the stalks before juice extraction by crushing, cutting, or shredding (Jankins, 1966). Stalk water content is important for juice extraction efficiency, with reduced efficiency when water content is less than 45% by weight. More sugar is extracted with repeated wetting and crushing following the initial expression. Juice extraction efficiency varies widely and it is important that the value used in estimating sugar yield from sweet sorghum be reported as in Table 2.

3.3 Sugar yield

In Louisiana U.S.A., stalk sugar concentration was 8.3 to 14.0% at flowering and 12.8 to 16.6% at soft dough, and total sugar yield was 4.3 to 8.5 Mg ha^{-1} at flowering and 6.6 to 11.7

Mg ha^{-1} at soft dough (Ricaud et al., 1979). Total sugar yield was 4.0 to 10.7 Mg ha^{-1} for several locations across the continental USA and up to 12 Mg ha^{-1} for Hawaii U.S.A. (Smith et al., 1987), equivalent to ethanol yields of 2129 to 5696 L ha^{-1} and comparable to ethanol yields with maize grain. Higher yields were reported for Florida U.S.A., ranging up to 17 Mg ha^{-1} (Vermerris et al., 2008). In the temperate U.S.A., sugar yields of sweet sorghum were as high as 6 Mg ha^{-1} with a sugar composition of 54% sucrose, 26% glucose, and 20% fructose (Smith & Buxton, 1993). Across seven site-years in Nebraska U.S.A. between 40.5 and 41.1° N latitude, sugar yield averaged 2.1 Mg ha^{-1} for a semi-arid site at 1300 m above sea level to 6.2 Mg ha^{-1} at lower altitude locations with a longer growing season.

Eventual commercialization of the conversion of cellulosic material to ethanol is likely to increase the value of sweet sorghum as a biofuel crop. In Kansas U.S.A., at 39.8° N latitude, calculated ethanol yields were 10,184, 6770, 7477, and 3073 L ha^{-1} for sweet sorghum, forage sorghum, maize, and perennial grass, respectively, when the total above-ground biomass was converted to ethanol (Propheter et al., 2010). Genetic improvement is also expected to result in increased productivity. Most research with sweet sorghum has been done with selected lines while significantly more yield potential was found in northern China with sweet sorghum hybrids (Zhao et al., 2009).

Sugar concentration along the length of sweet sorghum stalks is not uniform. The concentration of nonstructural carbohydrates in sweet sorghum was found to be 1.4 times higher in the upper and 2.7 times higher in the lower internodes compared with grain sorghum (Vietor & Miller, 1990). Sugar and sucrose concentration were found to be greater in the upper compared with the lower internodes at physiological maturity (Coleman, 1970). In another study, sugar concentration was highest at the seventh of 11 internodes (Krishnaveni et al., 1990). Stalk sugar concentration was usually higher at the middle stalk and least in the top 30-45 cm; the upper stem could be discarded in harvest without significant loss of sugar or juice yield (Janssen et al., 1930). Less concentration in older internodes may be due to less enzymatic activity compared with newer internodes, reducing their sink strength for sugar accumulation (Lingle, 1987). However, the mechanisms may be more complicated than enzymatic activities and sink strength and further investigation may be needed (Tarpley et al., 1994). Some cultivars partitioned a significant amount of carbohydrates to nodal tillers (Vietor & Miller, 1990).

3.4 Fermentation efficiency and ethanol yields

The theoretical yield of ethanol, which has a weight of 789 g L^{-1}, was determined to be 720, 646, 680, and 370 L Mg^{-1} for starch, glucose or fructose, sucrose, and maize grain, respectively (Smith & Buxton, 1993). They estimated that 5% of the sugar is used to produce microbial growth and non-ethanol products. Efficiency of maize grain conversion to ethanol has continued to improve. It was estimated at 417 L Mg^{-1} corn grain in 2005 (Wang et al., 2005). Dry-grind ethanol conversion of 423 L Mg^{-1} corn grain was common in the ethanol industry in 2009 (Table 2; Wortmann et al., 2010). Other energy yield estimates for comparison are 16 MJ kg^{-1} for biomass combustion, 18.5 MJ kg^{-1} for gasified wheat straw, ethanol yield of 0.36 L kg^{-1} of wheat, 18.3 MJ kg^{-1} for processing wheat to ethanol accounting for drying of the by-product, 7 MJ kg^{-1} of fresh bagasse of 50% dry weight, and 3.2 MJ kg^{-1} theoretical ethanol energy yield of fresh bagasse (Monti & Ventura, 2003), but these vary with conversion process and biomass composition (McAloon et al., 2000). Other conversion values are reported in Table 2.

Sweet sorghum juice can be converted to alcohol either by fermenting the juice or by fermenting the chopped stalks in a solid-state process (Rein, 1984). Alcohol conversion efficiency may be superior from chopped sweet sorghum than the corresponding juice. Fermentation efficiency can be improved by heating to 85^o C and the addition of yeast at any temperature. Adding yeast reduced the temperature effect on fermentation efficiency and alcohol yield was maximized by heating juice to 60^o C with addition of 0.25 g L^{-1} of yeast.
The U.S. Department of Energy estimated potential sweet sorghum ethanol yield to be 5590 L ha^{-1} (U.S. Department of Energy, 1979). Several sweet sorghum cultivars have the potential of producing greater than 25 Mg dm ha^{-1} $year^{-1}$ (Turhollow, 1994). In Iowa, ethanol yields of 11 sweet sorghum cultivars grown at six site-years ranged from 3850 to 4410 L ha^{-1} of ethanol production, assuming 95% extraction of sugars and 1.76 kg fermentable carbohydrate per liter of ethanol produced (Hunter, 1994). Other reported yields were 3050 to 4000 L ha^{-1} ethanol (Lueschen et al., 1991). Calculated ethanol yields were less in Nebraska U.S.A., averaging 1600 L ha^{-1} at a semi-arid location at 1300 m above sea level and ranging from 1800 to 4100 L ha^{-1} for locations with longer growing seasons and more precipitation (Wortmann et al., 2010).

3.5 Bi-product use

In addition to the ethanol produced by fermentation of sugar, other yield components of sweet sorghum may have biofuel or other value, including some grain yield and the bagasse remaining after juice extraction (Bennett & Anex, 2008). The grain and bagasse may be of value in animal feeding. The bagasse may be used in paper production, biofuel, or for soil application. Sweet sorghum hybrid varieties released in China have given biomass and grain yields of 25 and 5 Mg ha^{-1}, respectively, at a temperate latitude (Hong-Tu & Xiu-Ying, 1986).

3.6 Energy requirements and balances

Total energy yield, net energy yield, and the ratio of energy gained to energy input need to be considered in comparing biofuel sources and in comparing biofuel to fossil fuel (Table 2 and 3). The values used in these calculations vary and need to be reported in published works. The estimated crop production input of energy per liter of potential ethanol yield was 6.42, 5.25, 6.35, and 5.95 MJ L^{-1}, respectively, for maize, sweet sorghum, and sugar- and fodder beet grown in California U.S.A. (Reed et al., 1986). The respective theoretical ethanol yields are 4814, 5784, 7782, and 6886 L ha^{-1}. Estimated energy consumption for sweet sorghum compared to maize production in Nebraska U.S.A. was greater for fuel and transportation but less for N fertilizer and irrigation (Table 3; Wortmann et al., 2009). Energy required for converting the product to ethanol was not estimated.
The net energy gain was 17, 40 and 50% greater with sweet sorghum compared with fiber sorghum, wheat (*Triticum aestivum* L.) with no N, and wheat with N applied, respectively, assuming gasification of the crop residues (Monty & Venturi, 2003). The energy efficiency of ethanol production was estimated to be 90% compared with gasification.
The average energy output to input ratio was 2.83 for sweet sorghum across seven site-years in Nebraska U.S.A. compared to 2.13 and 2.21 for ethanol produced from grain of maize and grain sorghum, respectively (Table 3). Mean energy consumption for ethanol produced from sweet sorghum was approximately 3300 MJ ha^{-1} compared with 8900 and 5800 MJ ha^{-1} for maize and grain sorghum, respectively. These calculations were made using the BESS model

	Maize	Grain sorghum	Sweet sorghum
Grain or sugar yield, Mg ha^{-1}	7.94	6.24	2.85
N rate, kg ha^{-1}	107	50	0
Ethanol yield, L ha^{-1}	3361	2639	1892
Energy use rate, MJ L^{-1}	10.9	10.4	7.9
Energy yield, GJ ha^{-1} ††	78.3	60.9	39.9
Energy consumed, GJ ha^{-1}	36.6	27.5	14.5
Net energy yield, GJ ha^{-1} ††	41.6	33.4	25.3
Net energy ratio ††	2.13	2.21	2.70
Crop† energy use, MJ ha^{-1}	8932	5791	3294
Crop† CO_2 emission, kg Mg^{-1}	77.5	65.7	90.4
Crop† CH_4 emission, kg Mg^{-1}	0.080	0.070	0.073
Crop† N_2O emission, kg Mg^{-1}	0.38	0.26	0.98
Crop† CO_2e‡ emission, kg Mg^{-1}	192	144	385
Crop† CO_2e emission, g MJ^{-1}	21.5	16.2	27.4
Life cycle CO_2e emission, g MJ^{-1}	31.2	28.4	45.7
CO_2e reduction, %§ ††	66.1	69.1	48.8

† Values were calculated using the Biofuel Energy Systems Simulator (BESS; available at www.bess.unl.edu). Emission of N2O may be under-estimated for grain as the ethanol co-products were assumed to be fed to beef cattle, resulting in unnecessarily high protein rations with much excretion of urine-N that can be a significant source of N2O emission. This N2O emission was not considered in these calculations due to lack of good estimates.
‡ CO2e, total greenhouse gas emission expressed as CO2 equivalent.
§ This was calculated assuming 92 gCO2e emission MJ-1 for gasoline.
†† Grain crops included a standard energy and greenhouse gas co-product credit, while no co-product was included for sweet sorghum.

Table 3. Mean estimated yields, CO_2e emissions for grain and sugar produced, ethanol produced (g MJ^{-1}), and energy balances of maize, grain sorghum, and sweet sorghum determined over seven site-yr in Nebraska U.S.A. (adapted from Wortmann et al., 2010).

(Liska et al., 2009), and assumes processing in state-of-the-art ethanol plants and efficient use of the grain by-products in beef cattle feeding. In earlier work, the net energy ratio for sweet sorghum was estimated to exceed 2.0, with two units of energy recovered in the ethanol for each unit used for crop production and processing (Sheehan et al, 1978).

Mean net energy yield in the Nebraska U.S.A. study was 31 GJ ha^{-1} for sweet sorghum compared with 41 and 33 GJ ha^{-1} for maize and grain sorghum, respectively (Table 3; Wortmann et al., 2010). The mean reduction in greenhouse gas emission in replacing gasoline with ethanol produced from sweet sorghum as transportation fuel was 53%. The reduction may be greater because of uncertainty of the estimated N_2O emitted from decomposing bagasse, a major component of the greenhouse gas emission estimated on a carbon dioxide equivalent basis. In interpreting the results of comparing sweet sorghum with grain crops in Nebraska U.S.A., we must consider that grain crop production technology, including variety development, is much more advanced with the grain crops compared with sweet sorghum. Varietal differences indicated potential to increase productivity through genetic improvement. The potential of sweet sorghum hybrids compared with lines has been demonstrated (Zhao et al., 2009).

The cost ha^{-1} of sweet sorghum production was found to be greater than for maize in California U.S.A. because of high harvest costs (Geng et al., 1989), but hexose yield was greater with sweet sorghum and the costs of producing ethanol were very similar. In another study, the calculated cost of ethanol energy production was \$0.48, \$0.53, and \$0.58 L^{-1}, respectively, for maize, sugarcane, and sweet sorghum under best production potential scenarios in Florida U.S.A. (Rahmani & Hodges, 2006); processing and harvesting were major expenses for sweet sorghum. The cost of converting sugarcane juice to ethanol was estimated to be \$0.13 L^{-1} in Florida U.S.A. (Rahmani & Hodges, 2006); a similar cost may apply to converting sweet sorghum juice to ethanol.

4. Conclusion

There are several obstacles to the development of sweet sorghum as a competitive bio-energy crop for the U.S.A. Great Plains with greater challenges for the northern compared with the southern part of the region. The primary limitations of sweet sorghum for bioenergy in the U.S.A. Great Plains and other temperate climate zones include seasonality of harvest and large masses to be transported and stored. Fermentation of the expressed juice must be initiated quickly after harvest to avoid sugar loss. The loss of fermentable sugars from storing fresh juice at room temperature may be 20% after three days and up to 50% after one week, although losses were minimal with refrigerated storage (Wu et al., 2008; Wu et al., 2010). In temperate climates, the harvest window for sweet sorghum is limited by length of the growing season. Seed production is costly because of low seed yield and usually very tall plants. Few open-pollinated or hybrid cultivars are available for production, although there appears to be potential for significant increases in productivity in temperate zones with hybrid sweet sorghums (Zhao et al., 2009). Integration of distillation and distribution of sweet sorghum ethanol into existing grain-based ethanol processing systems would take advantage of existing infrastructure and reduce the challenges of transport and storage of sweet sorghum stalks or juice. Developing the means of stabilizing sweet sorghum juice to minimize sugar loss during storage would improve the feasibility of temperate zone sweet sorghum production. Profitable use of the bagasse such as with cellulosic ethanol production, without significant loss of nutrients for recycling in crop production, would add to the feasibility of sweet sorghum as a biofuel crop. Where bagasse is best returned to the land, combining small-scale processing technology, such as small-scale juice extraction, fermentation, and distillation linked with refinement at larger scale facilities, may reduce storage and transportation costs while enabling efficient nutrient recycling.

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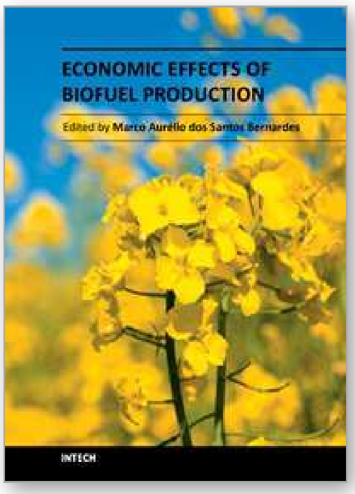

Economic Effects of Biofuel Production

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This book aspires to be a comprehensive summary of current biofuels issues and thereby contribute to the understanding of this important topic. Readers will find themes including biofuels development efforts, their implications for the food industry, current and future biofuels crops, the successful Brazilian ethanol program, insights of the first, second, third and fourth biofuel generations, advanced biofuel production techniques, related waste treatment, emissions and environmental impacts, water consumption, produced allergens and toxins. Additionally, the biofuel policy discussion is expected to be continuing in the foreseeable future and the reading of the biofuels features dealt with in this book, are recommended for anyone interested in understanding this diverse and developing theme.

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