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Review

Sweet sorghum as a bioenergy crop: Literature review

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ABSTRACT

Sweet sorghum (*Sorghum bicolor* L. Moench) is a widely adapted sugar crop with high potential for bioenergy and ethanol production. Sweet sorghum can yield more ethanol per unit area of land than many other crops especially under minimum input production. Sweet sorghum is well-adapted to marginal growing conditions such as water deficits, water logging, salinity, alkalinity, and other constraints. Sweet sorghum potential exists for ethanol yield of 6000 L ha^{-1} with more than three units of energy attained per unit invested. Traditionally, sweet sorghum has served as a syrup crop and its culture and production are well understood. Sweet sorghum is genetically diverse and variations exits for characteristics such as Brix % (13–24), juice sucrose concentration (7.2–15.5%), total stalk sugar yield (as high as 12 Mg ha^{-1}), fresh stalk yield (24–120 Mg ha^{-1}), biomass yield (36–140 t ha^{-1}) and others indicating potential for improvement. Transitioning sweet sorghum to a bioenergy crop is hampered by inadequate technology for large-scale harvest, transport and storage of the large quantities of biomass and juice produced, especially where the harvest window is short. Conversion of sweet sorghum to ethanol can be achieved by fermenting juice expressed from stems or directly fermenting chopped stalks. Integration of the fermentation and distillation of sweet sorghum juice in corn ethanol plants has not yet been achieved.

1. Introduction

Sweet sorghum is a widely adapted sugar crop with potential for bioenergy production. Sweet sorghum was introduced to the United States in the 1850s for syrup production [1]. Production peaked at about 136 million L yr^{-1} of syrup in 1946, substituting for sugar during World War II [2]. Sweet sorghum production declined steadily after the war because of low sugar prices coupled with inadequate advancement in harvesting and processing technology. Sweet sorghum is now of interest for ethanol production to be mixed with gasoline or to produce ethyl *tert*-butyl ether (ETBE), an octane additive to gasoline.

Sweet sorghum is often competitive with corn (*Zea mays* L.) and grain sorghum for ethanol yield when grain yield is less than 9 Mg ha^{-1}, and for water and nitrogen use efficiency [3]. Sweet sorghum can easily substitute for corn or grain sorghum in many annual cropping systems while adding to crop diversity.

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Currently most ethanol produced in the US is from corn grain with federal subsidies. Energy gains with production of ethanol from grain are modest typically ranging from 30% to 80%, depending partly on the efficiency of use of the distillers grain co-product. Sweet sorghum can be produced at less cost than corn with higher energy gains [3]. Rather than producing starch, sweet sorghum carbohydrates are stored in the stalk as sugar with sugar concentrations of 12–20% [4]. Sweet sorghum has the potential to produce up to 6000 L ha^{-1} of ethanol [2], equivalent to corn grain yields of approximately 20 Mg ha^{-1}. Sweet sorghum can yield more ethanol per unit area of land than many other common energy crops including corn (Table 1). Seasonal availability, the need to transport and maybe store much mass, and storability of sweet sorghum constrain sweet sorghum as a bioenergy crop.

2. Sweet sorghum production

The agronomic principles and production practices for sweet sorghum and grain sorghum are similar [2]. Sweet sorghum can produce grain as well as sugar. Reddy et al. [5] reported much diversity among sweet sorghum genotypes with ranges in India of 13–24% 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), 7.2–15.5% for sucrose concentration in juice, 24–120 Mg ha^{-1} for fresh stalk yield, 36–140 t ha^{-1} fresh biomass yield, and 27.1–47.6 Mg ha^{-1} mill-ready stalk yield. Plant height can be as tall as 480 cm [6] and stalks can be more than 45 mm thick [7].

Sweet sorghum is relatively well-adapted compared with corn to marginal growing conditions such as water deficit stress, water logging, salinity, alkalinity, and other edaphic constraints but yields are typically highest in deep, well-drained soils with good fertility. This adaptability and resilience often makes sweet sorghum more suited for biofuel than corn. After harvesting, the stalks of most cultivars can ratoon to produce another crop under suitable environments although ratoon yields are typically less than with first harvest.

2.1. *Planting date and length of growing period*

A base temperature of 13 °C has been used for calculating sweet sorghum growing degree days and thermal time [8,9].

Table 1 – Crop and ethanol yield of sweet sorghum compared to major potential energy crops (after Kersenbrock [57]).

Crop	Crop yield (Mg ha^{-1})	Ethanol yield (L ha^{-1})
Sugarcane	12.5[a]	5860
Sweet sorghum	7.60[a]	3560
Sugarbeet	7.10[a]	3300
Corn (grain)	5.70	2220
Grain sorghum (Grain)	3.70	1370
Wheat (grain)	2.00	790

[a] Yield is given in tones of fermentable sugars per hectare which is roughly 16% of the fresh plant weight.

Lueschen et al. [10] reported that rapid emergence and vigorous seedling growth occurs when soil temperature is above 18 °C at planting and that planting for mid-to-late September harvest maximized stalk Brix values in the upper Midwest.

Sugar yield is generally favored by earlier planting. Early planting increased yield significantly [8] and yield increased with increased radiation during the reproductive stage of the crop. Ricaud and Arenneaux [11] reported mean stalk yields across several cultivars in Louisiana to be 56 and 49 Mg ha^{-1} with 26 April and 25 May planting, respectively. 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 [8]. Juice yield was not affected by planting date in Mississippi but sugar yield was highest for early May planting [12] and similar for April and June planting [13]. Stalk and sugar yields were significantly depressed by delaying planting to mid June. In another study, delayed planting reduced dry matter yield but had little effect on Brix and sap content [10]. They found 13% higher fermentable carbohydrate and ethanol yields from earlier compared with later planting dates and recommended early planting of late-maturing sweet sorghum cultivars, despite the problem of lodging, for high sugar yields in the upper Midwest.

Sugar concentration of sweet sorghum increased as a function of the duration of growth and generally decreased with delayed planting irrespective of sampling stage [14,15]. Planting date can influence sugar yield by (i) altering phenology and development time since the rate of sugar accumulation is nearly constant and (ii) by the amount of radiation received during early reproductive growth, especially for genotypes with long pre-anthesis growth periods. Concentration and accumulation of sugars were near linear functions of either time of growth or the total radiation received. Long season, tall and thick stalk sweet sorghum cultivars were reported to be best for production of highly recoverable concentrated sugars [14,15]. Total intercepted radiation bracketing the growth stages of boot and early seed formation accounted for 75% of the variation in sweet sorghum yield [16].

2.2. *Plant population and stand establishment*

Uniform seedling emergence and stand establishment is important but relatively difficult to achieve for sweet sorghum because of small seed size and often low germination rate compared to grain sorghum, especially with constraints such as soil crusting, limited soil water after planting, uneven planting depth, weed competition, and insect pests. Poor stand establishment in sweet sorghum can lead to slow early growth. Agronomic management enhancing emergence and seedling establishment is critical. Sorghum has vigorous growth and is aggressively competitive after the fifth leaf stage.

In Turkey, biomass yield was more with 15 plants m^{-2} than with lower plant populations when sweet sorghum was planted in 65-cm rows [17]. Lueschen et al. [10] did not find an effect of seeding rate on sweet sorghum fermentable carbohydrate or ethanol yield. Ferraris and Charles-Edwards [8] found plant density effects on sugar concentration to be