CHAPTER

16

Sweet Sorghum for Biofuel Industry

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1. INTRODUCTION

Rapid increase in the global population and concomitant economic development, especially in Asia, are driving up the demand for energy, food, and feed. Continuing use of fossil fuels to meet this demand results in high levels of atmospheric pollution, fast depletion of fossil fuel reserves, and emission of greenhouse gases that contribute to global climate change. Renewable sources of energy, including solar, wind, and bioenergy, can help mitigate the negative effects associated with the use of fossil fuels and represent a growing share of the energy portfolio. Biofuels are of special interest because they are the only source of liquid transportation fuel that is both renewable and compatible with the existing fleet of vehicles. In addition, as biofuels originate from plant or algal biomass, their production can contribute to the economic development of rural economies. Usage of bioethanol blended with gasoline fuel for automobiles has the potential to significantly reduce petroleum use and reduce greenhouse gas (GHG) emissions (Balat and Balat, 2009).

Majority of currently produced, so-called first generation, bioethanol is produced via fermentation of monomeric sugars derived from crops such as sugarcane (Brazil), maize (United States), with cassava, sugar beet, and sweet potato being explored as alternatives in certain countries or regions (Reddy et al., 2008). The feedstocks from which bioethanol is currently produced are also used for human and animal consumption and other industries (industrial starch, cosmetics), and competition for these feedstocks is high (Jia et al., 2013). In addition to ethical concerns, generally framed as the "food versus fuel" debate (Chakravorty et al., 2009; Rosegrant and Msangi, 2014), the environmental benefits associated with the production of these feedstocks can be limited, depending on the input requirements (fertilizer, water, agrochemicals) (Farrell et al., 2006; Fargione et al., 2008). Therefore, alternative or supplemental feedstocks for bioethanol production are necessary during raw material shortage and for expansion of the industry (Shen et al., 2011). Ideally, these feedstocks are produced on low-productivity land, with minimal inputs, and from crops that are currently not used on a large scale for the production of food or feed. In addition, the use of agricultural crops in biobased economies represents a new use of these crops, which warrants the development of feedstocks with novel properties, either novel crops or existing crops optimized for biobased applications. Sweet sorghum has many attractive features that make it an excellent source of renewable energy (Rooney et al., 2007; Vermerris et al., 2007).

Sweet sorghum is defined as having a stalk containing sugar-rich juice, similar to sugarcane. The sugars in the juice are a mixture of sucrose, glucose, and fructose, with the exact ratio varying by genotype (Murray et al., 2009). The plants tend to be tall and produce grain. As such, sweet sorghum offers a solution to the food versus fuel debate: the grain can be used as food or feed, the sugars extracted from the stem can be fermented directly, and the resulting bagasse can be used as fodder to generate heat from burning it, as a lignocellulosic feedstock for the production of second-generation biofuels, or as a source of biogas when it is used in an anaerobic digester (Molaverdi et al., 2013; Whitfield et al., 2012). Thus, the diversion of crop land for cultivation of bioethanol crops (food versus fuel conflict) does not arise with sweet sorghum as it meets food, fuel, and fodder requirement (Chohnan et al., 2011; Rohowsky et al., 2013). Sweet sorghum−based ethanol production distilleries have been established in China and India.

Breeding Sorghum for Diverse End Uses
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2. MERITS OF SWEET SORGHUM OVER OTHER BIOFUEL CROPS

Sweet sorghum is a new generation bioenergy crop with highly efficient photosynthetic system (C_4) and is very efficient in the utilization of soil nutrients. It is a climate-resilient crop that matures earlier under high temperatures and short days. The crop can be grown for food, fuel, fodder, and fiber (a crop of four Fs). It is not only known as a "high-energy crop" because of its high photosynthetic rate but also called "the camel among crops" because of its drought resistance characteristics. Its wider adaptation (Reddy et al., 2008) and tolerance to various abiotic stresses such as drought (Tesso et al., 2005), water logging, and salinity (Almodares et al., 2008; Zegada-Lizarazu and Monti, 2012) along with higher water, nitrogen, and radiation use efficiencies make it a preferred biofuel feedstock over other crops such as corn, sugarcane, and sugar beet. It has a low water requirement of 8000 m^3/ha (over two crops annually), which is only 25% of that required for sugarcane and about half the quantity of water required by sugar beet (Table 16.1). It is seed propagated unlike sugarcane, which is propagated through setts. Given that water availability is poised to become major constraint to agricultural production in coming years (Ryan and Spencer, 2001), high input requiring cultivation of sugarcane becomes difficult and sweet sorghum offers a sustainable choice as it requires minimal water and purchased inputs.

Bioethanol from sweet sorghum can conserve the depleting fossil fuel resources and also help in reduction of GHG emissions. If the crop is used for the production of ethanol (from grains and sugar) and green electricity (from surplus bagasse), 3500 L crude oil equivalents can be saved per hectare cultivation area. If both food from grains and ethanol from the juice are produced, 2300 L crude oil equivalents can be saved per hectare cultivated area. Regarding GHG emissions, between 1.4 and 22 kg CO_2 equivalents can be saved depending on yields,

TABLE 16.1 Comparison of Sweet Sorghum With Other Bioethanol Feedstocks

Characteristics	Sugarcane	Sugar Beet	Corn	Sweet Sorghum
Crop duration	12–14 months	5–6 months	3–4 months	4 months
Growing season	One season	One season	All seasons	All seasons (depending on water availability)
Propagation soil requirement	Setts (40,000 ha^{-1}) grows well in drained soil	Seed (3.6 kg/ha; pellet) grows well in sandy loam; also tolerates alkalinity	Seed (8 kg/ha) grows well in sandy loam	Seed (8 kg/ha^{-1}) all types of drained soil
Water management	Requires water throughout the year (36,000 m^3/ha)	Requires water, 40%–60% compared with sugarcane (18,500 m^3/ha)	Requires water (12,000 m^3/ha)	Limited water requirement; can be grown as rain-fed crop (8000 m^3/ha)
Crop management	Requires intense management 250 to 400 kg/ha N-125 kg/ha P-125 kg/ha K	Requires moderate management 120 kg/ha N-60 kg/ha P-60 kg/ha K	Requires intense management 120 kg/ha N-60 kg/ha P-60 kg/ha K	Minimal management; low fertilizer 80–90 kg/ha N-40 kg/ha P
Yield (t/ha)	65–80 (Stalk)	85–100 (beet)	5–10 (grain)	40–55 for one cycle/year (stalk) 80–110 for two cycles/year (stalk)
Sugar content on weight basis (%)	10–12	15–18	n/a	7–12
Sugar yield (t/ha)	5–12	11–18	n/a	4–6 for one cycle/year 7–12 for two cycles/year
Ethanol yield from juice/grain (L/ha)	4350–7000	7100–10500	2150–4300	2000–3500 for one cycle/year 4000–7000 for two cycles/year
Harvesting	Harvested mechanically	Harvested mechanically	Harvested mechanically	Predominantly manual and mechanical harvesting at pilot scale

Modified from Vinutha, K.S., Rayaprolu, L., Yadagiri, K., Umakanth, A.V., Srinivasa Rao, P., 2014. Sweet sorghum research and development in India: status and Prospects. Sugar Tech. 16 (2), 133–143; Almodares, A., Hadi, M.R., 2009. Production of bioethanol from sweet sorghum: a review. Afr. J. Agric. Res. 4 (9), 772–780; Grassi, G., 2000. Bioethanol industrial world perspectives. In the Proceedings of 2000 1st World Conference on Biomass for Energy and Industry, pp. 2131–2134.

production methods, and the land cover prior to sweet sorghum cultivation (Köppen et al., 2009). The energy gain from sweet sorghum is substantially more than the energy used in production. The United States Department of Agriculture (USDA) reports that corn ethanol will produce 1.3–1.8 British thermal units (Btu) of energy for every Btu of fossil energy used in production, whereas sweet sorghum ethanol could produce as much as 12–16 Btu for every Btu used (https://www.uky.edu/Ag/CCD/introsheets/sorghumbiofuel.pdf).

The crop can also be used as feedstock for producing sugar, syrup, fodder, bedding, roofing, fencing, and paper in many areas of the world (Laopaiboon et al., 2007; Liu et al., 2008). The juice consisting of glucose, fructose, and sucrose is suitable for direct fermentation to ethanol (Sipos et al., 2009) or for production of other biobased chemicals (Wang et al., 2015; Ou et al., 2016). Leaves, bagasse, and grain portions of the crop can also be used to produce biofuels or can be used as animal feed. Bagasse can be burnt for heat or power generation or used to make valuable coproducts, such as pulp and particle board (Somani and Taylor, 2003). It can also be used as fodder for livestock or for cogeneration of power. The bagasse from sweet sorghum has a higher biological value than the bagasse from sugarcane when used as feed for animals, as it is rich in micronutrients and minerals (Blummel et al., 2009; Ashok Kumar et al., 2010). Besides this, the bagasse can also be used for the production of second-generation biofuels derived from the cellulose and hemicellulosic polysaccharides. Various processing options for sweet sorghum are shown in Fig. 16.1.

Besides ethanol, acetone, butanol, lactic acid, butyric acid, hydrogen, and methane are other fermentation products that can be produced. Sweet sorghum also produces several potential native products such as cellulose for paper production, waxes, proteins, and allelopathic compounds such as sorgoleone (Whitfield et al., 2012).

3. CHARACTERISTICS THAT MAKE SWEET SORGHUM AN ATTRACTIVE BIOFUEL FEEDSTOCK

3.1 Adaptability and Biomass Production

Sweet sorghum is an annual crop that is adapted to tropical and subtropical regions of all continents (except Antarctica). It can also be grown in temperate and semiarid regions of the world, suggesting high adaptability to different climates and soils (Davila-Gomez et al., 2011). Owing to its C_4 photosynthesis, sweet sorghum has a higher photosynthetic rate compared with C_3 grasses. Sorghum has small leaf surface area and highly developed root structure, which are likely responsible for the plant's exceptional drought tolerance (Damasceno et al., 2014). The crop only needs 300–375 mm (12–15 inches) of water per growing season. It has an extensive root system which goes 1.5–2.5 m deep and extends 1 m away from the stem for tapping more moisture. The crop remains dormant in the absence of sufficient water but does not wilt readily and recovers when sufficient moisture levels return (Gnansounou et al., 2005). It has the capacity to produce a crop with high biomass yield per hectare on marginal lands that are not suitable for food and feed production (Vermerris and Saballos, 2012) and has a high carbon assimilation (50 g/m^2 day). Sweet sorghum cultivars are often over 3 m tall and are able to produce biomass in the order of 58.3–80.5 tons of fresh stems per hectare in semiarid zones (Wang and Liu, 2009) and are usually late maturing and relatively photoperiod sensitive. Smith and Buxton (1993) reported that sweet sorghum gave an average fresh biomass yields of 89.2 and 65.5 t/ha for irrigated and dryland sites, respectively, when grown in a temperate climate. The primary and most essential component of biomass is the stalk, which contributes more than 70% of sweet sorghum biomass, and stalk weight is correlated with height, thickness, and juiciness (Audilakshmi et al., 2010). The fresh biomass production is an important productivity trait, and a strong association between fresh biomass production and ethanol yield per hectare was observed because the sugar-rich juice is extracted entirely from the biomass (Ritter et al., 2008).

3.2 High Water and Nitrogen Use Efficiencies

Sweet sorghum uses water and nitrogen more efficiently than corn (Geng, 1989; Smith and Buxton, 1993; Gnansounou et al., 2005; Bonin et al., 2016) and it requires less than 50% total nitrogen to produce similar ethanol yields as corn (Anderson et al., 1995; Damasceno et al., 2014).

3.3 Nonstructural Carbohydrate Content

Sweet sorghum accumulates large amounts of sugar (sucrose, glucose, and fructose) in stem parenchyma cells, beginning after completion of internode elongation (Hoffmann-Thoma et al., 1996) and peaking between anthesis

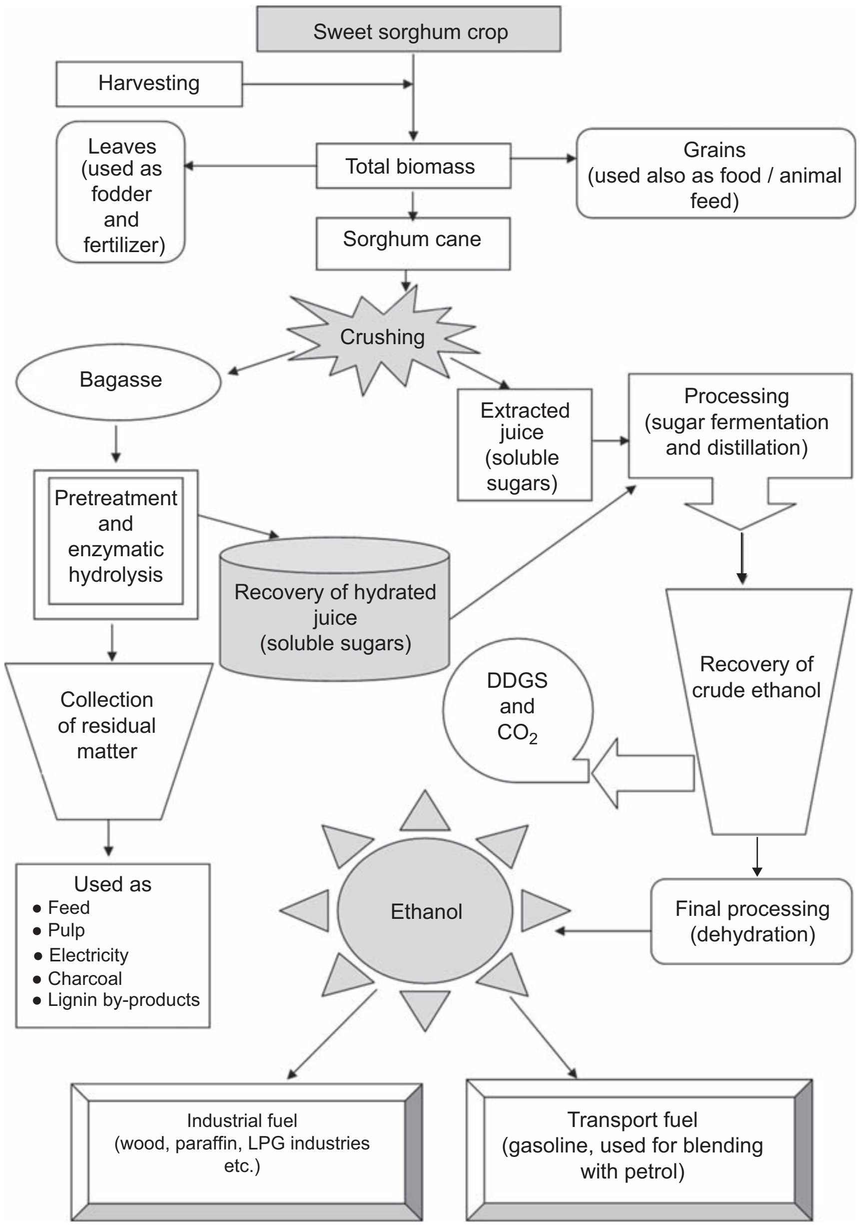

FIGURE 16.1 Various sweet sorghum processing options.

and physiological maturity (Pfeiffer et al., 2010). Tsuchihashi and Goto (2004) reported a high positive correlation between the °Brix value measured with a refractometer and total soluble solids (TSS) in the juice. Hence °Brix can be used as a convenient proxy for estimation of soluble sugar concentration in the juice, which is convenient when dealing with large number of genotypes that need to be evaluated.

Sweet sorghum is a very efficient source of bioenergy and it is highly imperative to breed new cultivars of sweet sorghum with high sugar content in combination with other desirable agronomic traits (Ali et al., 2008). Fermentable sugar concentration in the juice varies between 12% and 21% (Almodares and Hadi, 2009). Some sweet sorghum lines yield juice volumes as high as 78% of total plant biomass and contain soluble fermentable sugars ranging from 16% to 23% in comparison with sugarcane that has 14%–16% sugars (Grassi, 2000; Murray et al., 2009; Ratnavathi et al., 2011; Umakanth and Ashok Kumar, 2016). Genetic, environmental, and genetic × environment interactions all play a role in the inheritance of stem sugar concentration. Genetic variation for stalk biomass, °Brix and stalk weight in sweet sorghum, has been reported to be the result of both additive and nonadditive effects and depends in part on the sweet sorghum genotype being evaluated (Audilakshmi et al., 2010; Sanjana Reddy et al., 2011; Felderhoff et al., 2012).

TABLE 16.2 Juice Characteristics of Sweet Sorghum and Sugarcane

Character	Sweet Sorghum	Sugarcane
Sugar concentration in the juice (as °Brix)	10.5–20.7	16–20
Sucrose (%)	69–74	70–88
Proportion of sugar present as reducing sugars (%)	5–19	4–8
Starch (%)	0.4–5.3	0.001–0.05
pH	4.9–5.5	5.2–5.4
Titratable acidity[a]	3.6–4.8	2.0–3.2
Organic acids (%)	NA	1.5–5.5
Aconitic acid (%)	3.6–4.8	1.0–2.1
Protein (%)	0.9–1.3	0.5–0.6

[a]Titratable acidity is 0.1 mL NaOH required to adjust 10 mL juice to pH 8.3.
Modified from Lingle, S.E., 2010. Opportunities and challenges of sweet sorghum as a feedstock for biofuel. In: Eggleston, G. (Ed.), Sustainability of the Sugar and Sugar–ethanol Industries. ACS Symposium Series, vol. 1058. American Chemical Society, Washington, DC, pp. 177–188.

3.4 Juiciness of Stalks

Unlike grain sorghum, sweet sorghum accumulates large amounts of juice in the stalks. The stalks containing juice are crushed to extract the juice similar to that of sugarcane. Juice content varies between 12,000 and 20,000 L/ha depending on genotype, soil, and weather conditions. Compared with sugarcane, sweet sorghum has higher reducing sugar content and lower nonreducing sugars, i.e., sucrose (Table 16.2). Ethanol is produced from sweet sorghum stem juice through fermentation technology as similar with molasses-based process using same infrastructure used for sugarcane industry. Furthermore, the juice can be boiled to make a sugar syrup of 70–80 °Brix, which can be used as table syrup (as in the United States) or as a feedstock for biofuel production. In addition to high juice extractability, important juice-related traits are sugar composition, clarity (high starch content causes the juice to be cloudy), and color.

3.5 Sugar and Ethanol Yields

Unlike from grain starch, ethanol production from sugar does not require energy to depolymerize carbohydrates and thus lowers cost for energy production as compared with grain alcohol production. Being a sugar crop, sweet sorghum has been found to be competitive with corn for theoretical ethanol yield with less energy invested (Smith et al., 1987; Smith and Buxton, 1993; Hunter and Anderson, 1997). Up to 13.2 tons/ha of total sugars, equivalent to 7682 L of ethanol per hectare, can be produced by sweet sorghum under favorable conditions (Jackson et al., 1980; Murray et al., 2009). Smith et al. (1987) reported total sugar yield of sweet sorghum ranging from 4 to 10.7 Mg/ha for the continental United States and up to 12 Mg/ha for Hawaii, whereas Smith and Buxton (1993) reported sugar yields at 6 Mg/ha in Iowa and Colorado. Theoretical ethanol yield estimates have generally ranged from 3000 to 4000 L/ha (Lueschen et al., 1991). Approximately 50–85 t/ha of sweet sorghum stalks yield 39.7–42.5 t/ha of juice, which on fermentation yields 3450–4132 L/ha ethanol (Serna-Saldivar et al., 2012). Similar ethanol production levels, 3296 L/ha (Kim and Day, 2011) and 4750–5220 L/ha (Wu et al., 2010), were reported in different studies. Hunter and Anderson (1997) estimated the ethanol yield potential to be as high as 8000 L/ha. In yet another study in the United States, the highest theoretical ethanol yields for sweet sorghum averaged 10,616 and 11,408 L/ha in 2005 and 2006, respectively (Bonin et al., 2016).

4. GENETIC ENHANCEMENT OF SWEET SORGHUM

The primary goal in any sweet sorghum genetic enhancement programs is development of parental lines with all the desirable traits for development of elite hybrids and varieties. In general, emphasis is on development of sweet sorghum as a novel dual-purpose bioenergy feedstock, which can be utilized for sugar-based and cellulosic biofuels. Breeding programs target the following objectives (modified from Rao et al., 2013).

1. Developing male-sterile and restorer lines having high stalk sugar content, juice yields, resistance to shoot pests and diseases, and high grain yields
2. Photoperiod- and thermoinsensitive sweet sorghums that can be grown throughout the year and fit into diversified cropping systems
3. Sweet sorghum genotypes with variable maturities, which can widen the harvesting window so that the sweet sorghum stalk supplies can be scheduled appropriately to the industry for crushing
4. Sweet sorghum genotypes with high digestibility of residues when used as single-cut forage

4.1 Genetics of Biofuel Traits

A single dominant gene was found to be conferring the nonsweet character (Ayyangar et al., 1936), which was confirmed by the findings of Guiying et al. (2000) and Ritter et al. (2007) who reported stalk sugar to be governed by recessive genes with additive and dominance effects. On the contrary, existence of multiple genes with additive effects was reported by Li et al. (2004). Audilakshmi et al. (2010) reported sugar concentration in stalk to be controlled by dominant genes, and the traits associated with high ethanol production, i.e., stalk yield, plant height, and juice yield, were governed by overdominance.

Continuous variation in the amount of extractable juice was observed in juicy genotypes and inbred progeny of juicy × dry lines, suggesting that multiple genes may be involved in controlling the trait (Saballos, 2008). Predominant role of nonadditive gene action for plant height, stem girth, TSS, millable stalk yield, and extractable juice yield was observed, which indicates the importance of heterosis breeding for improving these traits (Sankarapandian et al., 1994). Inheritance of stalk biomass, brix, and stalk weight in sugar stalk was subject to both additive gene effect and nonadditive gene effect but mainly controlled by nonadditive genes (Zhou et al., 2005). This suggests exploiting heterosis breeding for developing high-biomass sweet sorghum hybrids with higher levels of brix, stalk, and juice yields provided that one of the parents is tall and has sweet stalk and high juice yields.

5. CULTIVARS RELEASED IN DIFFERENT COUNTRIES

Utilizing the commonly used breeding approaches such as the pedigree method of selection and backcross breeding, several sweet sorghum cultivars were developed in different countries and tested in pilot-scale trials for ethanol production. In Brazil, EMBRAPA (EmpresaBrasileira de PesquisaAgropecuária; Brazilian Corporation of Agricultural Research) began a program for the development of sweet sorghum cultivars in the 1970s. Initially, 50 genotypes of the USDA, Africa, and India were introduced and had their agronomic traits assessed and served as the basis for the development of novel germplasm. EMBRAPA has registered and released sweet sorghum varieties such as BR 501, BR 506, BRS 508, BRS 509, and BRS 511. In China, 17 promising sweet sorghum hybrids have been released so far nationally (Rao et al., 2015). The Shenyang Agricultural University bred new hybrids of sweet sorghum for use as feedstock for ethanol production. Grain and sugar production have been improved for Shennong Tianza No. 1, 2, and 3 sweet sorghum hybrids. Ji-2731 is a Chinese accession with cold tolerance, while E-Tian is a Russian sweet sorghum line with high biomass, intermediate stem sugar, and cold tolerance. In India, promising nationally released cultivars for cultivation are SSV 84, CSV 19SS, CSV 24SS, and hybrid CSH 22SS besides state releases such as SSV 74, RVICSH 28, and Phule Vasundhara. These cultivars are known to have high stalk and sugar yields, as well as tolerance to important pests.

In the United States, Theis, Keller, Dale, and M81E were the important sweet sorghum cultivars developed at the US Sugar Crops Field Station at Meridian, Mississippi, before it was closed in 1983. The USDA also operated a sweet sorghum breeding program in the Rio Grande Valley in Texas, which led to cultivars such as Rex, Rio, and Wray. In 2007, the University of Kentucky and the University of Nebraska jointly released a male-sterile hybrid named KN Morris. Public sweet sorghum breeding programs also exist at several other universities and USDA research facilities in the United States, including Florida, Georgia, and South Carolina.

6. STATUS OF COMMERCIALIZATION AND INDUSTRIAL EXPERIENCES FOR PRODUCTION OF BIOFUELS

Brazil: In Brazil, sweet sorghum is currently being included in the ethanol industry with the proposal as source of feedstock in addition to sugarcane (Renan et al., 2016), and the country has announced that it considers sweet sorghum a strategic crop. Energy crop companies Ceres, Inc. and Syngenta have entered an agreement that stimulates sorghum adoption, and new hybrids were introduced, which averaged over 80 tons/ha. These companies intend to work together to support the introduction of sweet sorghum as a source of fermentable sugars at Brazil's 400 ethanol mills. Large-scale sweet sorghum pilot trials are being conducted by EMBRAPA, Ceres, Inc., Chromatin, Inc., Advanta, Inc., and Dow Agro Sciences. The Government of Brazil is very keen in encouraging sweet sorghum plantations for biofuel production and has identified 1.8 million ha for sweet sorghum plantations to augment fuel grade ethanol production (Rao et al., 2015).

The United States: In the United States, several companies have tested the potential of sweet sorghum juice as an ethanol feedstock. The economic feasibility of producing sweet sorghum as an ethanol feedstock in the south eastern United States was analyzed, and it was found that production costs were consistently lower compared with competing crops such as corn, cotton, and soybean (Linton et al., 2011). In 2012, Delta BioRenewables, LLC collaborated with Commonwealth AgriEnergy, LLC to use sweet sorghum sugars to produce ethanol at Commonwealth's corn ethanol plant located in Hopkinsville, Kentucky. The Commonwealth ethanol facility has used sweet sorghum sugar as an ethanol input instead of corn without significant changes in the process (University of Kentucky Cooperative Extension Service, 2013). Efforts in western Tennessee, coordinated by the company Bio Dimensions, have also focused on the evaluation of sweet sorghum as a biofuel crop. In Florida, where sugarcane is currently cultivated, sweet sorghum can be cultivated as a supplementary crop, as was described for Brazil. Highlands EnviroFuels, LLC has been planning to construct biorefinery that utilizes sweet sorghum and sugarcane, whereas Southeast Renewable Fuels, LLC started the construction of a dedicated sweet sorghum–based biorefinery. Both companies have experienced delays due to the current low price of oil and natural gas and lack of political support in the state for biofuels. Initiatives in several other states, including Texas, Louisiana, Oklahoma, and Iowa, are considering sweet sorghum for ethanol production.

Central America: A Central American case study on techno-economic analysis of integrating sweet sorghum into sugar mills revealed that a sugar mill operating 2 months during off-season could obtain an average revenue of US$ 3M for a crushing rate of 6500 tons/day (Cutz and Santana, 2014).

China: China is one of the leading countries researching and developing sweet sorghum as a nonfood feedstock for fuel ethanol. The first commercial plant with sweet sorghum as a feedstock was approved and established in Inner Mongolia in 2012. According to the data from this plant, the feedstock costs accounted for approximately 80% of the total ethanol production costs, resulting in a poor economic performance. Recently, farmers in North China demonstrated the feasibility of sweet sorghum plantations for ethanol fermentation in regions with vast areas of marginal land (Liu et al., 2015). A few industries such as ZTE Energy Company Ltd. (Inner Mongolia), Fuxin Green BioEnergy Corporation, Xinjiang Santai Distillery, Liaoning Guofu Bioenergy Development Company Ltd., Binzhou Guanghua Biology Energy Company Ltd., Jiangxi QishengyuanAgri-Biology Science and Technology Company Ltd., Jilin Fuel Alcohol Company Ltd., and Heilongjiang Huachuan Siyi Bio-fuel Ethanol Company Ltd. either conducted large-scale sweet sorghum processing trials or are in the commercialization stage (Rao et al., 2015).

Australia: In Australia, a study on harvesting, transporting, and trial crushing of sweet sorghum in a sugar mill reported a sugar extraction efficiency of 70%–80%. By changing operational settings at the mill, efficiencies similar to those observed for sugarcane could be obtained (Webster et al., 2004). A joint study by the industry partner Agri-Fuels Ltd. and the Australian Government through the Rural Industries Research and Development Corporation suggested that sweet sorghum has a large potential cropping area, including tropical and subtropical Queensland, Northern Territory, and Western Australia, as well as in temperate regions of New South Wales, Victoria, and Western Australia. High ethanol yields from the fermentation of sweet sorghum juice were achieved with efficiencies as high as 95% of theoretical yield under laboratory-scale conditions (Albertson et al., 2013). Addition of sweet sorghum juice to sugarcane juice resulted in higher ethanol yields. At the Mackay Renewable Biocommodities Pilot Plant, pilot-scale studies of the pretreatment, enzymatic hydrolysis, and fermentation of carbohydrates from sweet sorghum bagasse were undertaken. The study revealed that ethanol yields from the fermentation of sugars derived from cell wall polysaccharides were between 99.1% and 118.0% of the initial glucose contents of the fermentation substrates.

India: Indian Institute of Millets Research (IIMR), which is the premier research institute to conduct sorghum research under the National Agricultural Research System in India, has conducted several pilot-scale studies in different states of India in collaboration with sugarcane distilleries. Between 2001 and 2006, joint activities were carried out with M/S Renuka Sugars, Belgaum; Sagar Sugars, Chittoor; Praj Industries, Pune; National Sugar Institute, Kanpur; Somaiya Organo-chemicals, Sakarwadi; India Glycols Ltd., Kashipur; KCP Sugars, Lakshmipuram; Nav Bharat Ventures, Samalkot. The ethanol yields ranged from 35 to 40 L/ton of crushed sweet sorghum stalks (Rao et al., 2014). A test at a large mill with 356 tons of sweet sorghum stalks was conducted with a sugar factory in Karnataka. The realized extraction efficiency was 50% with an ethanol yield of 39 L/ton of crushed stalks (Hunsigi et al., 2010).

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) through its Agribusiness Incubator has used sweet sorghum for ethanol production in partnership with Rusni Distilleries (Rusni), which is claimed to be the world's first sweet sorghum−based ethanol production distillery with a capacity of 40 kL per day (KLPD). This distillery, which started its commercial ethanol production in June 2007 (Vinutha et al., 2014), reported an ethanol yield of 45 L/ton of crushed stalks (Basavaraj et al., 2012). M/s Tata Chemicals, Ltd. started a sweet sorghum−based distillery with a capacity of 30 KLPD at Nanded, Maharashtra, with the technical support from ICRISAT and IIMR. It operated between 2008 and 2010 using sweet sorghum as a feedstock for ethanol production and produced 90 KL of transport-grade ethanol during 2010. Neither of these distilleries could continue because of the unfavorable ethanol procurement price prevailing that time and the challenges ensuring a reliable supply of feedstock.

The National Policy on Biofuels of India (2009) identified sweet sorghum as one of the candidate crops for augmenting biofuel production in the country, and sugar industries are exploring the possibilities of complementing their existing molasses-based ethanol production with alternative raw material to fill-in the lean period of sugarcane crushing for year-round operations. The Government of India recently raised the procurement price of ethanol to Rs. 48.50−49.50 per liter to meet its blending mandate of 10% ethanol with gasoline. The use of sweet sorghum as biofuel feedstock in existing sugar mills is going to be a win-win situation for both industry and resource-poor dryland sweet sorghum farmer, while improving the environment in terms of reduction of emissions and reducing the country's cost of oil imports. Under Indian conditions, sweet sorghum could be cultivated and supplied during the lean period of sugarcane crushing (Fig. 16.2), thus extending the crushing period before and after sugarcane crushing and stretch the sugar mill operation.

Several sugar industries are currently testing the feasibility of sweet sorghum complementing the ethanol production from sugarcane molasses in India. The Government of India, through its Department of Biotechnology, is funding a project aimed at commercialization of sweet sorghum as a complementary feedstock for ethanol production in the sugar mills.

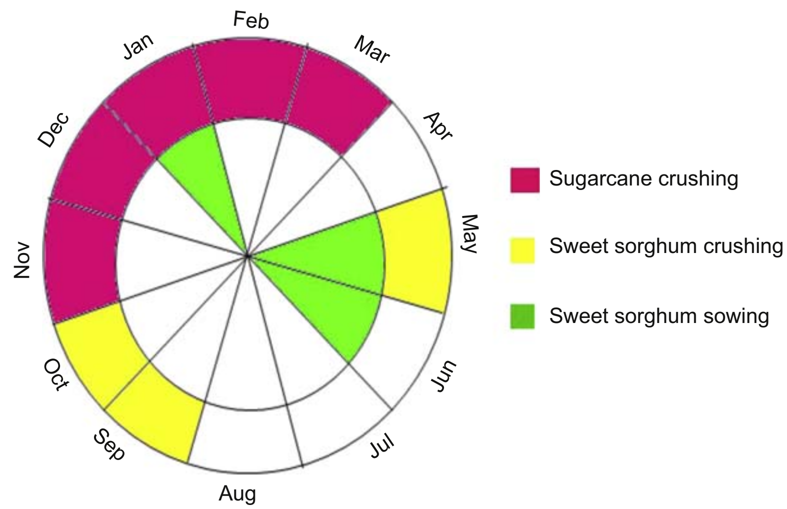

FIGURE 16.2 Scheduling the sweet sorghum feedstock availability during lean period of sugarcane crushing. *Adapted from Umakanth, A.V., Ashok Kumar, A., 2016. Sweet sorghum - a novel opportunity for biofuel production. Indian Farming. 65 (12), 37−40.*

Africa: In the southern African region, Zambia, Mozambique, South Africa, and Malawi have a high potential for sweet sorghum–based ethanol production (Watson et al., 2008; Zhao et al., 2009). Woods (2001) summarized the results of two full-scale industrial processing trials carried out in Zimbabwe employing sweet sorghum varieties "Keller" and "Cowley." The ethanol yield was reported as 3000 L/ha. In Mozambique and Angola, a number of foreign and few domestic investments on land deals for production of sweet sorghum as biofuel feedstock are underway.

Philippines: San Carlos Bioenergy Inc. became the first commercial distillery to process sweet sorghum bioethanol in Southeast Asia under the Philippine Department of Agriculture and produced 14,000 L of fuel-grade ethanol in 2012. The Ecofuels distillery at San Mariano, Isabela, with an output of 300 KLPD, is planning to use sugarcane and sweet sorghum as feedstocks for commercial ethanol production.

7. SECOND-GENERATION BIOFUEL DEVELOPMENT FROM SWEET SORGHUM

As mentioned before, sweet sorghum bagasse can be considered as a lignocellulosic feedstock for the production of ethanol. In that case, the bagasse needs to be pretreated and subjected to enzymatic saccharification to generate fermentable sugars from cellulose and hemicellulosic polysaccharides, which will include pentoses that require the use of suitable fermenting organisms. The conversion of cell wall polysaccharides to fermentable sugars is hampered by the presence of the aromatic cell wall polymer lignin. Lignin forms a physical barrier that restricts access to cellulose, and the cellulolytic enzymes can irreversibly adhere to the lignin. Furthermore, pretreatment of lignin results in compounds that are toxic to the fermenting microbes. The *brown midrib* (*bmr*) mutants of sorghum, first described by Porter et al. (1978), have significantly lower levels of lignin. Enzymatic saccharification of pretreated biomass from several *bmr* mutants has been shown to generate 7%–21% higher yields of fermentable sugars relative to the corresponding wild-type sorghums (Saballos et al., 2008). The conversion efficiency of biomass from a *bmr6*–*bmr12* double mutant was even greater than that of the individual single mutants (Dien et al., 2009). Several additional *bmr* mutants generated by the USDA-ARS in Lubbock, Texas (Xin et al., 2008, 2009), also showed promise as lignocellulosic feedstocks (Sattler et al., 2014; Scully et al., 2016). From these various analyses, it also became apparent, however, that some *bmr* mutants do not perform better (Sattler et al., 2014) or sometimes even worse (Saballos et al., 2008) than the wild-type control.

Introgression of the *bmr* alleles into sweet sorghum was shown to have positive effect on biomass conversion efficiency, which will enhance the utility of sweet sorghum as a dual-purpose crop that can generate fermentable sugars from both juice and bagasse. This type of biomass can be converted under milder pretreatment conditions (lower temperature and/or shorter residence times), which reduces the cost of the biomass conversion process. Efforts are underway in several countries to introgress *bmr* alleles into elite sweet sorghum cultivars. The *bmr* mutations can, however, also have detrimental effects on the integrity of the stalk and increase the incidence of stem lodging and susceptibility to pests and diseases. The reduced yield can counteract the benefits of the *bmr* mutations in the processing phase.

Photoperiod-sensitive high sugar genotypes that yield high amounts of biomass may also be of interest. These plants remain in the vegetative phase until the day length is shorter than approximately 12 h. When such genotypes are cultivated in subtropical and temperate regions, large amounts of biomass can be generated. In addition, the use of such genotypes also extends the harvest season, which results in a longer period of feedstock availability to the biorefinery. In sorghum, photoperiod sensitivity is controlled by maturity (*ma*) genes at six independent loci (Murphy et al., 2011, 2014). The strategic use of complementary *ma* alleles can result in photoperiod-insensitive parents that, when crossed, produce photoperiod-sensitive hybrid offspring (Rooney and Aydin, 1999).

8. CONCERNS IN SWEET SORGHUM PROMOTION AND STRATEGIES FOR REALIZING HIGHER PRODUCTIVITY

In general, complementation of sweet sorghum with sugarcane is possible in those areas of the world where sugarcane is produced, as sweet sorghum is compatible with the infrastructure and the managerial expertise available in the sugarcane industry. However, sweet sorghum has some critical issues that need to be addressed for realizing higher productivity.

8.1 Biomass Availability

Constant availability of biomass during most part of the year is the major demand of any biomass-based biofuel industry. Lack of availability of the required quantity of sweet sorghum feedstock during sugarcane's off-season is a major constraint. There is a need to develop germplasm with high biomass and sugar yields per unit time and per unit inputs applied for production under different agro-climatic situations. This is feasible through exploitation of the available genetic resources from different regions of the world. In addition, there is a need to breed cultivars with different maturities (i.e., early, medium, and late), which will broaden the harvest window and cater to the industrial need over a longer period (Burks et al., 2013). For tropical and subtropical regions, the goal of breeding would be to achieve three or four crops in a year to increase annual biomass yields (Anami et al., 2015). The feedstock supply can be extended by using cultivars with different maturities, extension of planting time and seasons, planting in wider geographical areas, establishment of decentralized crushing units, and widening the harvest window.

8.2 Photoperiod- and Thermosensitivity and Genotype × Environment Interaction

Sweet sorghum is adapted to latitudes ranging from 40°N to 40°S and comes up well in drylands with annual rainfall ranging from 550 to 800 mm under a variety of soil and climatic conditions. It can be grown in areas where the temperature ranges from 15 to 45°C, but the optimum temperature for growth lies between 25 and 40°C. The day length requirement is 10–14 h. There is season specificity in sweet sorghum, which necessitates breeding of separate cultivars for different seasons. The genotype–environment interaction greatly influences the success of any breeding strategy, as the significant interaction of location (environment) with the cultivars has been demonstrated (Wortmann et al., 2010). Under Indian conditions, sweet sorghum lines grown in post–rainy season result in decreased yields compared with rainy and summer seasons because of shorter day length and lower night temperatures (Umakanth and Ashok Kumar, 2016). As the global climate is gradually changing to elevated temperatures and as sweet sorghum is bound to occupy new niches, there is a need to identify/develop sweet sorghum cultivars that are photoperiod- and thermoinsensitive, with high stalk and sugar yields and which can be grown across seasons for ensuring a year-round supply of feedstock to the industry. In addition, appropriate crop production practices that extend the feedstock availability for longer periods are required. Conversion of sorghum genotypes to adapt to long-day conditions has increased genetic diversity and greatly contributed to improved grain crop quality and productivity (Marguerat and Bahler, 2010). In view of biofuel production, characterization of sweet sorghum growing areas should be based on interactions between soil, climate, genotype, and the quantity and quality of the feedstock.

8.3 Biotic and Abiotic Stress Resistance

Shoot fly (*Atherigona soccata* Rondani) and stem borer (*Chilo partellus*) are the major pests that reduce sorghum production in many parts of the world. Of these, the spotted stem borer, *C. partellus*, is predominant in the Indian subcontinent and south and eastern Africa, causing serious damage to sorghum (Jotwani and Young, 1972; Singh and Rana, 1989). It attacks sweet sorghum from 2 weeks after germination until crop harvest and affects all plant parts (Fig. 16.3), especially affecting the juice quality.

Incorporation of resistance through conventional and molecular approaches, especially to key shoot pests such as shoot fly, stem borer, shoot bug, aphids, and midge, which affect seed production, should be an integral part of any sweet sorghum breeding program. Bt technology is helpful in the control of stem borer, and promising levels of resistance to stem borer in grain sorghums are reported (Visarada et al., 2016). In a 3-year study (2009–12) on identification of sweet sorghum accessions with multiple resistance to shoot fly and spotted stem borer at IIMR (erstwhile Directorate of Sorghum Research), Hyderabad, India, the lines IS 5353, IS 18164, ICSV 93046, ICSV 700, and GGUB 50 were classified as resistant to both pests (Shyam Prasad et al., 2015). These can be used in future sweet sorghum breeding programs for genetically enhancing the levels of resistance to these key pests. Besides this, breeding for tolerance to abiotic stresses such as heat, postflowering drought, salinity, cold, and flooding should also be addressed in breeding. For northern China and southern Europe, chilling tolerance is a favorable trait for early seed germination and seedling growth (Anami et al., 2015). Kaoliang sorghums from China are reported as sources for tolerance to cold temperatures at germination and seedling stages (Qingshan and Dahlberg, 2001) and could be exploited in breeding programs.

FIGURE 16.3 Stem borer–infested sweet sorghum stalks.

8.4 Hybrid Parents With High Sugar Content

Present-day sweet sorghum varieties are mostly line cultivars (Pfeiffer et al., 2010), as the sugar content is an additive, nonheterotic trait (Makanda et al., 2009; Pfeiffer et al., 2010; Felderhoff et al., 2012), and there is a scarcity of short-statured A-lines with sweet stem (Pedersen et al., 2013). Sweet sorghum parental line development needs immediate attention for enhancing the genetic potential of females for high sugar content and resistances. Genetic enhancement of the crop for increased sugar yield is very critical to make sweet sorghum more profitable to the farmers and the industry, while sustaining grain yield. As sugar accumulation and sugar yield are quantitative traits controlled by polygenes and significantly affected by the environment (Shiringani et al., 2010), suitable strategies and success of breeding can be based on partitioning the agronomic traits and sugar components. While hybrid sweet sorghums offer the prospect of greater sugar, grain, and biomass yield, their development takes more time than the development of new cultivars, in part, because hybrid sweet sorghum production requires three lines: the male-sterile A-line used as female; the R-line that provides the pollen; and the maintained B-line that is used to generate more A-line seed. The same genetic and environmental constraints (pest and disease resistance, photoperiod- and thermosensitivity, adaptation to the soil) apply to these different lines. From an economic perspective, hybrid seed needs to be purchased new every season, which is convenient to the seed producer, but it represents a recurring cost to the farmers compared with seed from cultivars, which can be saved for the next season. However, hybrids are more preferable over line cultivars because of their higher yields and a predictable maturity that helps to schedule the cane supplies to the industry.

8.5 Juice Quality and Storage Losses

Self-fermentation of juice inside the stalk due to high invertase activity in sweet sorghum is a major concern with the time lag between harvest and juice extraction. Qualitative and quantitative deterioration of stalks after harvest affects the sustainability of sweet sorghum as a biofuel crop. Losses of fermentable sugars up to 20% from storing fresh juice at room temperature for about 3 days and up to 50% loss during 1 week of juice storage were reported (Ratnavathi et al., 2011). If the time lag between harvesting and milling of the sorghum stalk is between 2 and 4 days, then it leads to huge losses in the recoverable sugars because of deterioration and souring of the harvested stalk (Ganesh Kumar et al., 2013). A way to prevent the sugars in the juice from getting degraded is to boil the juice, which also concentrates it, although this represents an input of energy. Genetic variation for key traits related to juice quality have been identified, and entries SPSSV 30, ICSV 25275, ICSV 25280, and SPV 422 are recommended for delayed harvesting, as the sugar levels are sustained for a longer time (Kumar et al., 2010). Additional research on the postharvest losses in terms of juice quality and quantity would be helpful.

8.6 Mechanization

Sweet sorghum in developing countries requires huge labor investment for harvesting and leaf stripping. Much more refinement in harvesting machinery is needed to reduce the harvesting cost and drudgery in harvesting operation. This would also help in reducing the cost of cultivation and time lag between harvesting and postharvest operations, thus making sweet sorghum a viable biofuel crop. Further refinement in crushing technology is also needed to reach the targeted recovery.

8.7 Policy Support for Farmers and Industry

Governments need to provide incentives to farmers and industry for promoting sweet sorghum as an efficient feedstock for biofuel production. These incentives may be in the form of input subsidies or cash to the farmers for encouraging sweet sorghum cultivation and providing required permits and capital assistance for setting up of machinery for start-up industries wishing to crush alternate feedstocks such as sweet sorghum. It is always desirable to establish industries based on multiple feedstocks rather than a single feedstock, as it provides longer periods of mill operation for producing bioethanol.

9. WAY FORWARD

Public attention across the world is focused on biofuels to reduce GHG emissions and dependence on foreign oil. Sweet sorghum with its proven ability to grow under diverse environments has the potential for providing a good source of fermentable sugars from stalks and grain for producing bioethanol using first- and second-generation ethanol production technologies. In the context of climate change, sweet sorghum outperforms other crops as an attractive climate-resilient crop to produce ethanol, generate power, and reduce carbon emissions produced from fossil fuel utilization. One of the obstacles to this crop's expansion as a biofuel feedstock is the fact that sugarcane has established dominance over the production chain of sugar and ethanol and is receiving the majority of the investments. However, sweet sorghum is rapidly expanding and has a great potential for further growth. In countries such as China, India, United States, Brazil, Iran, Italy, and Spain, this crop is considered a promising feedstock for ethanol production, and many research projects have been developed with it in these countries (Almodares et al., 2008; Wortmann et al., 2010; Renan et al., 2016). Significant investments are being made in the synthesis of biobased products using processes other than traditional fermentation. Future research should focus on fine tuning tools for mechanical harvesting of both grain and fresh stalks in a single pass. Prominence should also be on the optimization of sweet sorghum as an energy crop through conventional breeding and with aid of molecular tools for enhanced productivity and stress tolerance utilizing the genetic resources without a significant impact on food supplies and the natural environment.

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References

Albertson, P., Wong, H.H., Moghaddam, L., Stolz, W., Harrison, M.D., O'Hara, I.M., 2013. Energy products from sweet sorghum. In Sweet sorghum - opportunities for a new, renewable fuel and food industry in Australia. In: Australian Government-Rural Industries Research and Development Corporation (RIRDC) Publication No. 13/087, pp. 38−61.

Ali, M.L., Rajewski, J.F., Baenziger, P.S., Gill, K.S., Eskridge, K.M., Dweikat, I., 2008. Assessment of genetic diversity and relationship among a collection of US sweet sorghum germplasm by SSR markers. Mol. Breed. 21, 497−509.

Almodares, A., Hadi, M.R., 2009. Production of bioethanol from sweet sorghum: a review. Afr. J. Agric. Res. 4 (9), 772−780.

Almodares, A., Hadi, M.R., Ahmadpour, H., 2008. Sorghum stem yield and soluble carbohydrates under phenological stages and salinity levels. Afr. J. Biotechnol. 7, 4051−4055.

Anami, S.E., Zhang, L.M., Xia, Y., Yu-Miao, Z., Zhi-Quan, L., Hai-Chun, J., 2015. Sweet sorghum ideotypes: genetic improvement of the biofuel syndrome. Food Energy Secur. 4 (3), 159−177.

Anderson, I.C., Buxton, D.B., Hallam, A., Hunter, E., 1995. Biomass Production and Ethanol Potential from Sweet Sorghum, vol. 4. Leopold Center for Sust. Agric., Iowa State Univ., Ames, IA, pp. 97−101.

Ashok Kumar, A., Reddy, B.V.S., Blümmel, M., Anandan, S., Reddy, Y.R., Reddy, Ch.R., Srinivasa Rao, P., Reddy, P.S., 2010. On-farm evaluation of elite sweet sorghum genotypes for grain and stover yields and fodder quality. Anim. Feed Sci. Technol. 10S, 69−78.

Audilakshmi, S., Mall, A.K., Swarnalatha, M., Seetharama, N., 2010. Inheritance of sugar concentration in stalk (brix), sucrose content, stalk and juice yield in sorghum. Biomass Bioenergy 34 (6), 813−820.

Ayyangar, G., Ayyar, M., Rao, V., Nambiar, A., 1936. Mendelian segregation for juiciness and sweetness in sorghum stalk. Madras Agric. J. 24, 247−248.

Balat, M., Balat, H., 2009. Recent trends in global production and utilization of bioethanol. Appl. Energy 8, 2273−2282.

Basavaraj, G., Parthasarathy Rao, P., Kaushik, B., Reddy, Ch, R., AshokKumar, A., Srinivasa Rao, P., Reddy, B.V.S., 2012. Assessing viability of bio-ethanol production from sweet sorghum. In: Working Paper Series No. 30, RP − Markets, Institutions and Policies. International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India. Patancheru 502 324 20 pp.

Blummel, M., Rao, S.S., Palaniswami, S., Shah, L., Reddy, B.V.S., 2009. Evaluation of sweet sorghum (*Sorghum bicolor* L. Moench) used for bio-ethanolproduction in the context of optimizing whole plant utilization. Anim. Nutr. Feed Technol. 9, 1−10.

Bonin, C.L., Heaton, E.A., Cogdill, T.J., Moore, K.J., 2016. Management of sweet sorghum for biomass production. Sugar Tech. 18 (2), 150−159.

Burks, P.S., Felderhoff, T.J., Viator, H.P., Rooney, W.L., 2013. The influence of hybrid maturity and planting date on sweet sorghum productivity during a harvest season. Agron. J. 105, 263−267.

Chakravorty, U., Hubert, M.-H., Nøstbakken, L., 2009. Fuel versus food. Ann. Rev. Res. Econ. 1 (1), 645−663. http://doi.org/10.1146/annurev.resource.050708.144200.

Chohnan, S., Nakane, M., Rahman, M.H., Nitta, Y., Yoshiura, T., Ohta, H., Kurusu, Y., 2011. Fuel ethanol production from sweet sorghum using repeated-batch fermentation. J. Biosci. Bioeng. 111, 433−436.

Cutz, L., Santana, D., 2014. Techno-economic analysis of integrating sweetsorghum into sugar mills: the Central American case. Biomass Bioenergy 68, 195−214.

Damasceno, B.M.C., Schaffert, E.R., Dweikat, I., 2014. Mining genetic diversity of sorghum as a bioenergy feedstock, plants and bioenergy. Adv. Plant Biol. 4, 81−106.

Davila-Gomez, F., Chuck-Hernandez, C., Perez-Carrillo, E., Rooney, W., Serna-Saldivar, S., 2011. Evaluation of bioethanol production from five different varieties of sweet and forage sorghums (*Sorghum bicolor* (L) Moench). Ind. Crops Prod. 33, 611−616.

Dien, B.S., Sarath, G., Pedersen, J.F., Sattler, S.E., Chen, H., Funnell-Harris, D.L., Nichols, N.N., Cotta, M.A., 2009. Improved sugar conversion and ethanol yield for forage sorghum (*Sorghum bicolor* L. Moench) lines with reduced lignin contents. Bioenergy Res. 2 (3), 153−164. https://doi.org/10.1007/s12155-009-9041-2.

Fargione, J., Hill, J., Tilman, D., Polasky, S., Hawthorne, P., 2008. Land clearing and the biofuel. Carbon debt. Science 319, 1235−1238.

Farrell, A.E., Plevin, R.J., Turner, B.T., Jones, A.D., O'Hare, M., Kammen, D.M., 2006. Ethanol can contribute to energy and environmental goals. Science 311, 506−508. Correction published in Science 312, 1748.

Felderhoff, T.J., Murray, S.C., Klein, P.E., Sharma, A., Hamblin, M.T., Kresovich, S., Vermerris, W., Rooney, W.L., 2012. QTLs for energy-related traits in a sweet × grain sorghum [*Sorghum bicolor* (L.) Moench] mapping population. Crop Sci. 52, 2040−2049.

Ganesh Kumar, C., Nageswara Rao, R., Srinivasa Rao, P., Ahmed, K., Ashok Kumar, A., Ravinder Reddy, Ch., Reddy, B.V.S., 2013. Assessing sweet sorghum juice and syrup quality and fermentation efficiency. In: Reddy, B.V.S., Ashok Kumar, A., Reddy, Ch. R., Parthasarathy Rao, P., Patil, J.V. (Eds.), Developing a Sweet Sorghum Ethanol Value Chain. Patancheru 502 324. International Crops Research Institute for the Semi-Arid Tropics, Andhra Pradesh, India, ISBN 978-92-9066-555-7. Order Code: CPE 172. 240 pp.

Geng, S., 1989. Potential yields and on-farm ethanol production cost of corn, sweet sorghum, fodder beet, and sugar beet. J. Agron. Crop Sci. 162, 21.

Gnansounou, E., Dauriat, A., Wyman, C.E., 2005. Refining sweet sorghum to ethanol and sugar: economic trade-offs in the context of North China. Bioresour. Technol. 96 (9), 985−1002.

Grassi, G., 2000. Bioethanol industrial worldperspectives. In: In the Proceedings of 2000 1st World Conference on Biomass for Energy and Industry, pp. 2131−2134.

Guiying, L., Weibin, G., Hicks, A., Chapman, K.R., 2000. A Training Manual for Sweet Sorghum. FAO/CAAS/CAS, Bangkok, Thailand.

Hoffmann-Thoma, G., Hinkel, K., Nicolay, P., Willenbrink, J., 1996. Sucrose accumulation in sweet sorghum stem internodes in relation to growth. Physiol. Plant 97, 277−284.

Hunsigi, G., Yekkeli, N.R., Kongawad, B.Y., 2010. Sweet stalk sorghum: An alternative sugar crop for ethanol production. Sugar Tech. 12, 79−80. https://doi.org/10.1007/s12355-010-0017-5.

Hunter, E.L., Anderson, I.C., 1997. Sweet sorghum. In: Janick, J. (Ed.), Horticultural Reviews, vol. 21. John Wiley and Sons, New York, NY, pp. 73−104.

Jackson, D.R., Arthur, M.F., Davis, M., Kresovich, S., Lawhon, E.S., Lipinsky, W.T., Rudolph, A., 1980. Research Report on Development of Sweet Sorghum as an Energy Crop, vol. 1. Agricultural Task. US DOE, US Department of Commerce, Battele, Columbus.

Jia, F., Chawhuaymak, J., Riley, M.R., Zimmt, W., Ogden, K.L., 2013. Efficient extraction method to collect sugar from sweet sorghum. J. Biol. Eng. 7, 1−8.

Jotwani, M.G., Young, W.R., 1972. Recent developments in chemical control of insect pests of sorghum. In: Rao, N.G.P., HouseLR (Eds.), Sorghum in Seventies. Oxford & IBH Publishing, New Delhi, India, pp. 251−256.

Kim, M., Day, D., 2011. Composition of sugar cane, energy cane, and sweet sorghum suitable for ethanol production at Louisiana sugar mills. J. Ind. Microbiol. Biotechnol. 38 (7), 803−807.

Köppen, S., Reinhardt, G., Gärtner, S., 2009. Assessment of Energy and Greenhouse Gas Inventories of Sweet Sorghum for First and Second Generation Bioethanol, 77 pp..

Kumar, C.G., Fatima, A., Srinivasa Rao, P., Reddy, B.V.S., Rathore, A., Nageswar Rao, R., Khalid, S., Kumar, A.A., Kamal, A., 2010. Characterization of improved sweet sorghum genotypes forbiochemical parameters, sugar yield and its attributes at different phenological stages. Sugar Tech. 12, 322−328.

Laopaiboon, L., Thanonkeo, P., Jaisil, P., Laopaiboon, P., 2007. Ethanolproduction from sweet sorghum juice in batch and fed-batch fermentations bySaccharomyces cerevisiae. World J. Microbiol. Biotechnol. 23, 1497−1501.

Li, G., Gu, W., Chapman, K., 2004. Sweet Sorghum. China Agricultural Science and Technology Press, Beijing, China.

Lingle, S.E., 2010. Opportunities and challenges of sweet sorghum as a feedstock for biofuel. In: Eggleston, G. (Ed.), Sustainability of the Sugar and Sugar−ethanol Industries. ACS Symposium Series, vol. 1058. American Chemical Society, Washington, DC, pp. 177−188.

Linton, J.A., Miller, J.C., Little, R.D., Petrolia, D.R., Coble, K.H., 2011. Economic feasibility of producing sweet sorghum as an ethanol feedstock in the south-eastern United States. Biomass Bioenergy 35, 3050−3057.

Liu, R., Li, J., Shen, F., 2008. Refining bioethanol from stalk juice of sweet sorghumby immobilized yeast fermentation. Renew. Energy 33, 1130−1135.

Liu, H., Ren, L., Spiertz, H., Zhu, Y., Xie, G.H., 2015. An economic analysis of sweet sorghum cultivation for ethanol production in North China. GCB Bioenergy 7, 1176−1184. https://doi.org/10.1111/gcbb.12222).

Lueschen, W.E., Putnam, D.H., Kanne, B.K., Hoversted, T.R., 1991. Agronomicpractices for production of ethanol from sweet sorghum. J. Prod. Agric. 4, 619−625.

Makanda, I., Pangirayi, T., Detera, J., 2009. Combining ability andheterosis of sorghum germplasm for stem sugar traits under off-season conditions in tropical lowland environments. Field Crops Res. 114, 272−279.

Marguerat, S., Bahler, J., 2010. RNA-seq: from technology to biology. Cell. Mol. Life Sci. 67, 569−579.

Molaverdi, M., Karimi, K., Khanahmadi, M., Goshadrou, A., 2013. Enhanced sweet sorghum stalk to ethanol by fungus Mucorindicus using solid state fermentation followed by simultaneous saccharification and fermentation. Ind. Crops Prod. 49, 580−585.

Murphy, R.L., Klein, R.R., Morishige, D.T., Brady, J.A., Rooney, W.L., Miller, F.R., Dugas, D.V., Klein, P.E., Mullet, J.E., 2011. Coincident light and clock regulation of *pseudoresponse regulator protein 37 (PRR37)* controls photoperiodic flowering in sorghum. Proc. Natl. Acad. Sci. 108, 16469−16474.

Murphy, R.L., Morishige, D.T., Brady, J.A., Rooney, W.L., Yang, S., Klein, P.E., Mullet, J.E., 2014. Ghd7 (Ma6) represses sorghum flowering in long days: Ghd7 alleles enhance biomass accumulation and grain production. Plant Genome 7.

Murray, S.C., Rooney, W.L., Hamblin, M.T., Mitchell, S.E., Kresovich, S., 2009. Sweet sorghum genetic diversity and association mapping for brix and height. Plant Genome 2, 48−62.

Ou, M.S., Awasthi, D., Nieves, I., Wang, L., Erickson, J., Vermerris, W., Ingram, L.O., Shanmugam, K.T., 2016. Sweet sorghum juice and bagasse as feedstocks for the production of optically pure lactic acid by native and engineered *Bacillus coagulans* Strains. Bioenergy Res. 9, 123−131. http://doi:10.1007/s12155-015-9670-6.

Pedersen, J.F., Sattler, S.E., Anderson, W.F., 2013. Evaluation of public sweet sorghum A-lines for use in hybrid production. Bioenergy Res. 6, 91−102.

Pfeiffer, T.W., Bitzer, M.J., Toy, J., Pedersen, J.F., 2010. Heterosis in sweet sorghum and selection of a new sweet sorghum hybrid for use in syrup production in Appalachia. Crop Sci. 50, 1788−1794. https://doi.org/10.2135/cropsci2009.09.0475.

Porter, K.S., Axtell, J.D., Lechtenberg, V.L., Colenbrander, V.F., 1978. Phenotype, fiber composition, and in vitro dry matter disappearance of chemically induced *brown midrib (bmr)* mutants of sorghum. Crop Sci. 18, 205−208.

Qingshan, L., Dahlberg, J.A., 2001. Chinese sorghum genetic resources. Econ. Bot. 55, 401−425.

Rao, P.S., Umakanth, A.V., Reddy, B.V.S., Dweikat., I., Bhargava., S., Kumar, G., Braconnier, C.S., Patil, J.V., 2013. Sweet sorghum: genetics, breeding and commercialization. In: Singh, B.P. (Ed.), Biofuel Crops: Production, Physiology and Genetics. CAB International, pp. 172−198.

Rao, S.S., Patil, J.V., Dayakar Rao, B., Ratnavathi, C.V., Umakanth, A.V., Mishra, J.S., Chapke, R.R., 2014. Current status of sweet sorghum biofuel industrial experiences forpilot−production of bioethanol. In: Proceedings of Model Training Course on "Improved Sorghum Cultivation and Value-addition Perspective Samprdquosemicolon 22−29 Sept., 2014. DSR, Hyderabad, ISBN 81-89335-50-2, pp. 1−6.

Rao, P.S., Prakasham, R.S., Parthasarathy Rao, P., Chopra, S., Jose, S., 2015. Sorghum as a sustainable feedstock for biofuels. In: Jose, S., Bhaskar, T. (Eds.), Biomass and Biofuels - Advanced Biorefineries for Sustainable Production and Distribution. CRC Press, Taylor & Francis Group, Boca Raton, FL, pp. 27−47.

Ratnavathi, C., Chakravarthy, S., Komala, V., Chavan, U., Patil, J., 2011. Sweet sorghum as feedstock for biofuel production: a review. Sugar Tech. 13 (4), 399−407.

Reddy, B.V.S., Ramesh, S., Kumar, A.A., Wani, S.P., Ortiz, Ceballos, H., Sreedevi, T.K., 2008. Bio-fuel crops research for energy security and rural development in developing countries. Bioenergy Res. 1, 248−258. https://doi.org/10.1007/s12155-008-9022-x.

Renan, Silva e Souza, Rafael Augusto, da Costa Parrella, Vander, Fillipe de Souza, Nádia Nardely Lacerda Durães Parrella, 2016. Maturation curves of sweet sorghum genotypes. Cienc. E Agrotecnol. 40 (1), 46−56.

Ritter, K.B., McIntyre, C.L., Godwin, I.D., Jordan, D.R., Chapman, S.C., 2007. An assessment of the genetic relationship between sweet and grain sorghums, within *Sorghum bicolor* ssp. *bicolor* (L.) Moench, using AFLP markers. Euphytica 157, 161−176.

Ritter, K.B., Jordan, D.R., Chapman, S.C., Godwin, I.D., Mace, E.S., McIntyre, C.L., 2008. Identification of QTL for sugar-related traits in a sweet × grain sorghum [*Sorghum bicolor* (L.) Moench] recombinant inbred population. Mol. Breed. 22, 367−384. https://doi.org/10.1007/s11032-008-9182-6.

Rohowsky, B., HaBler, T., Gladis, A., Remmele, E., Schieder, D., 2013. Feasibilityof simultaneous saccharification and juice co-fermentation on hydrothermalpretreated sweet bagasse for ethanol production. Appl. Energy 102, 211−219.

Rooney, W.L., Aydin, S., 1999. Genetic control of a photoperiod-sensitive response in *Sorghum bicolor* (L.) Moench. Crop Sci. 39, 397−400.

Rooney, W.L., Blumenthal, J., Bean, B., Mullet, J.E., 2007. Designing sorghum as a dedicated bioenergy feedstock. Biofuels Bioprod. Biorefining 1, 147−157.

Rosegrant, M.W., Msangi, S., 2014. Consensus and contention in the food-versus-fuel debate. Annu. Rev. Environ. Resour. 39 (1), 271−294. http://doi.org/10.1146/annurev-environ-031813-132233.

Ryan, J.G., Spencer, D.C., 2001. Future Challenges and Opportunities for Agricultural R&D in the Semi-arid Tropics. Patancheru 502324 83pp.. International Crops Research Institute for the Semi −Arid Tropics, Andhra Pradesh, India.

Saballos, A., 2008. Development and utilization of sorghum as a bioenergy crop. In: Vermerris, W. (Ed.). Genetic Improvement of Bioenergy Crops. Springer-Verlag, New York, pp. 211−248.

Saballos, A., Vermerris, W., Rivera, L., Ejeta, G., 2008. Allelic association, chemical characterization and saccharification properties of *brown midrib* mutants of sorghum (*Sorghum bicolor* (L.) Moench). Bioenergy Res. 1 (3−4), 193−204. http://doi.org/10.1007/s12155-008-9025-7.

Sanjana Reddy, P., Reddy, B.V.S., Srinivasa Rao, P., 2011. Genetic analysis of traits contributing to stalk sugar yield in sorghum. Cereal Res. Commun. 39 (3), 453–464.

Sankarapandian, R., Ramalingam, J., Pillai, M.A., Vanniarajan, C., 1994. Heterosis and combining ability studies for juice yield related characteristics in sweet sorghum. Ann. Agric. Res. 15, 199–204.

Sattler, S.E., Saballos, A., Xi, Z., Funnell-Harris, D.L., Vermerris, W., Pedersen, J.F., 2014. Characterization of novel sorghum *brown midrib* mutants from an EMS-mutagenized population. G3 Genes Genomes Genet. 4, 2115–2124.

Scully, E.D., Gries, T., Funnell-Harris, D.L., Xin, Z., Kovacs, F.A., Vermerris, W., Sattler, S.E., 2016. Characterization of novel *Brown midrib 6* mutations affecting lignin biosynthesis in sorghum. J. Integr. Plant Biol. 58 (2), 136–149. http://doi.org/10.1111/jipb.12375.

Serna-Saldivar, S.O., Cristina, C., Esther, P., Erick, H., 2012. Sorghum as a multifunctional crop for the production of fuel ethanol: current status and future trends. In: Lima, M.A.P. (Ed.), Bioethanol. http://www.intechopen.com/books/bioethanol/sorghum-as-a-multifunctional-crop-for-the-production-offuel-ethanol-current-status-and-future-trend.

Shen, F., Zeng, Y., Deng, S., Liu, R., 2011. Bioethanol production from sweet sorghum stalk juice with immobilized yeast. Proc. Environ. Sci. 11, 782–789.

Shiringani, A.L., Frisch, M., Friedt, W., 2010. Genetic mapping of QTLs for sugar-related traits in a RIL population of *Sorghum bicolor* L. Moench. Theor. Appl. Genet. 121, 323–336.

Shyam Prasad, G., SrinivasaBabu, K., Subbarayudu, B., Bhagwat, V.R., Patil, J.V., 2015. Identification of sweet sorghum accessions possessing multiple resistance to shoot fly (*Atherigonasoccata*Rondani) and spotted stem borer (*Chilopartellus*Swinhoe). Sugar Tech. 17 (2), 173–180.

Singh, B.U., Rana, B.S., 1989. Varietal resistance in sorghum tospotted stem borer (*Chilopartellus*Swinhoe). Insect Sci. Its Appl. 10, 3–27.

Sipos, B., Réczey, J., Somorai, Z., Kádár, Z., Dienes, D., Réczey, K., 2009. Sweet sorghum as feedstock for ethanol production: enzymatic hydrolysis of steam-pretreated bagasse. Appl. Biochem. Biotechnol. 153, 151–162.

Smith, G.A., Buxton, D.R., 1993. Temperate zone sweet sorghum ethanol production potential. Bioresour. Technol. 43, 71–75.

Smith, G.A., Bagby, M.O., Lewellan, R.T., Doney, D.L., Moore, P.H., Hills, F.J., Campbell, H.J., Hogaboam, G.J., Coe, G.E., Freeman, K., 1987. Evaluation of sweet sorghum for fermentable sugar production potential. Crop Sci. 27 (4), 788–793.

Somani, R.B., Taylor, J.R.N., 2003. Sorghum: a potential source of raw material for agro-industries. In: Alternative Uses of Sorghum and Pearl Millet in Asia. CFC Technical Paper No. 34. Proceedings of the Expert Meeting, Patancheru, Andhra Pradesh, India, 1–4 July 2003. ICRISAT, Patancheru, Andhra Pradesh, India. Common Fund for Commodities, Amsterdam, Netherlands, pp. 146–168.

Tesso, T.T., Claflin, L.E., Tuinstra, M.R., 2005. Analysis of stalk rot resistance and genetic diversity among drought tolerant sorghum genotypes. Crop Sci. 45, 645–652. https://doi.org/10.2135/cropsci2005.0645.

Tsuchihashi, V., Goto, Y., 2004. Cultivation of sweet sorghumand determination of its harvest time to make use as the rawmaterial for fermentation, practiced during rainy season in dryland of Indonesia. Plant Prod. Sci. 7, 442–448.

Umakanth, A.V., Ashok Kumar, A., 2016. Sweet sorghum - a novel opportunity for biofuel production. Indian Farm. 65 (12), 37–40.

Vermerris, W., Saballos, A., 2012. Genetic enhancement of sorghum for biomass utilization. In: Paterson, A.H. (Ed.), Genomics of the Saccharinae. Springer, New York, pp. 391–425.

Vermerris, W., Saballos, A., Ejeta, G., Mosier, N.S., Ladisch, M.R., Carpita, N.C., 2007. Molecular breeding to enhance ethanol production from corn and sorghum stover. Crop Sci. 47, S-142–S-153.

Vinutha, K.S., Rayaprolu, L., Yadagiri, K., Umakanth, A.V., Srinivasa Rao, P., 2014. Sweet sorghum research and development in India: status and Prospects. Sugar Tech. 16 (2), 133–143.

Visarada, K.B.R.S., Prasad, G.S., Royer, M., 2016. Genetic transformation and evaluation of two sweet sorghum genotypes for resistance to spotted stemborer, *Chilo partellus* (Swinhoe). Plant Biotechnol. Rep. 10, 277–289.

Wang, F., Liu, C.Z., 2009. Development of an economic refining strategy of sweet sorghum in the inner Mongolia region of China. Energy Fuels 23, 4137–4142.

Wang, L., Ou, M.S., Nieves, I., Erickson, J.E., Vermerris, W., Ingram, L.O., Shanmugam, K.T., 2015. Fermentation of sweet sorghum derived sugars to butyric acid at high titer and productivity by a moderate thermophile *Clostridium thermobutyricum* at 50°C. Bioresource Technol. 198, 533–539. http://doi.org/10.1016/j.biortech.2015.09.062.

Watson, H., Garland, G., Purchase, B., Dercas, N., Griffee, P., Johnson, F., 2008. Bioenergy for sustainable development and global competitiveness: the case of sugar cane in southern Africa. In: A Compilation of Results from the Thematic Research Network: Cane Resources Network for Southern Africa (CARENSA). Thematic Report 1: Agriculture. http://www.carensa.net/tr/CARENSA-TR1-Agriculture_final.pdf.

Webster, A.J., Hoare, C.P., Sutherland, R.F., Keating, B.A., 2004. Observations of the harvesting, transporting and trial crushing of sweet sorghum in a sugar mill. Proc. Aust. Soc. Sugar Cane Technol. 2004 (26), 2004.

Whitfield, M.B., Chinn, M.S., Veal, M.W., 2012. Processing of materials derived from sweet sorghum for biobased products. Ind. Crops Prod. 37 (1), 362–375.

Woods, J., 2001. The potential for energy production using sweet sorghum in southern Africa. Energy Sustain. Dev 2001 (5), 31–38.

Wortmann, C.S., Liska, A., Ferguson, R.B., Lyon, D.J., Klein, R., Dweikat, I., 2010. Dryland performance of sweet sorghum and grain crops for biofuel in Nebraska. Agron. J. 102, 319–326.

Wu, X., Staggenborg, S., Propheter, J.L., Rooney, W.L., Yu, J., Wang, D., 2010. Features of sweet sorghum juice and their performance in ethanol fermentation. Ind. Crops Prod. 31 (1), 164–170.

Xin, Z., Wang, M.L., Barkley, N.A., Burow, G., Franks, C., Pederson, G., Burke, J., 2008. Applying genotyping (TILLING) and phenotyping analyses to elucidate gene function in a chemically induced sorghum mutant population. BMC Plant Biol. 8, 103.

Xin, Z., Wang, M.L., Burow, G., Burke, J., 2009. An induced sorghum mutant population suitable for bioenergy research. Bioenergy Res. 2 (1), 10–16.

Zegada-Lizarazu, W., Monti, A., 2012. Are we ready to cultivate sweet sorghum as a bioenergy feedstock? A review on field management practices. Biomass Bioenergy 40, 1–12.

Zhao, Y., Dolat, A., Steinberger, Y., Wang, X., Osman, A., Xie, G., 2009. Biomass yield and changes in chemical composition of sweet sorghum cultivars grown for biofuel. Field Crops Res. 111 (1–2), 55–64.

Zhou, H., Zuhu, D., Jun, L., Zhang, M., 2005. Analysis on combining ability for the energy sugar stalk breeding. Acta Agric. Univ. Jiangxiensis 27 (2), 14–20.