Sweet Sorghum: From Theory to Practice

P. Srinivasa Rao, C. Ganesh Kumar and Belum V. S. Reddy

Abstract Sweet sorghum [*Sorghum bicolor* (L.) Moench] is a multipurpose crop (food, feed, fodder and fuel) that has the potential as an alternative biofuel feedstock without impacting food and fodder security. This chapter entitled "Sweet sorghum: From theory to practice" discusses on the historical developments in sweet sorghum and immense range of genetic variability that was available in major sorghum regions of the world. The candidate feedstock characteristic traits of sweet sorghum *vis-a-vis* other major biofuel feedstocks like sugarcane, corn and sugar beet were compared. Sweet sorghum fares well in many aspects as it is a C_4 species with greater resilience to diverse agro-ecologies, low fertilizer and water requirement besides short lifecycle. Hence, many consider it as climate change ready crop; some consider it as miracle crop and few term it as a smart crop. A quantitative insight into the production-ecological sustainability of sweet sorghum biofuel feedstock production systems has been discussed. The ongoing R&D efforts at ICRISAT as well as in National Agricultural Research System (NARS) on sweet sorghum value chain were highlighted. The breeding efforts in Brazil, USA and China on this crop are briefly narrated.

Keywords Sweet sorghum · Biofuels · Semi-arid tropics · C_4 plant · Jowar · Agronomy · Taxonomy, food—fuel trade off

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P. S. Rao and C. G. Kumar (eds.), *Characterization of Improved Sweet Sorghum Cultivars*, SpringerBriefs in Agriculture,
DOI: 10.1007/978-81-322-0783-2_1,

1 Introduction

Sorghum (*Sorghum bicolor* L. Moench) is a C_4 herbaceous annual grass that is cultivated from the seed, and is known by various names like great millet and guinea corn in West Africa, kafir corn in South Africa, durra in Sudan, mtama in Eastern Africa, jowar in India, kaoliang in China and milo or milo-maize in the United States (Purseglove 1972). It has wide flat leaves and a round or elliptical panicle with full of grain at maturity. The plant accumulates high concentrations of soluble sugars (10–15 %) in the plant stalk sap or juice. It is a crop of high universal value since it can be cultivated in tropical, subtropical, temperate, and semi-arid regions as well as in poor quality soils of the world. It is termed as "the sugarcane of the desert" or "the camel among crops" due to its drought hardy characteristics (Sanderson et al. 1992).

The name "sweet sorghum" is used to identify those varieties of sorghum, *Sorghum bicolor* (L.) Moench, which has juicy and sweet stalks. Sweet sorghum is mainly cultivated for syrup production or forage, whereas other sorghum varieties such as kafirs and milos are cultivated for grain. Other sorghum-types include the broomcorn-type sorghum (*Sorghum dochna* var. *technicum* (Koern.) Snowden), whose head/panicle is used for making brooms and brushes; while johnsongrass, *Sorghum halepense* (L.) Pers. and sudangrass, *Sorghum sudanense* (Piper) Stapf. are grown primarily for forage purpose.

2 History

Sorghum is a grass of Old World origin and *Sorghum vulgare* Pers. is a native wild plant of Africa that is drought-resistant and heat-tolerant member of the grass family and many of the varieties under cultivation in the recent history have originated from that continent. Documented evidence indicated that sorghum was grown in Assyria as early as 700 BC (Ziggers 2006). Wide varieties in the genus *Sorghum* were observed in the North Eastern regions of Africa comprising of Ethiopia and Sudan in Eastern Africa (Doggett 1988). Around 200 AD or even earlier, sorghum made its way into Eastern Africa from Ethiopia via the local tribes, who cultivated this crop mainly for grain and the sweet cane was chewed for pleasure and nutrition. Later, the Bantu tribe carried this crop with them to the Savannah regions of Western and Southern Africa who used the grain mainly for making beer. The Bantu tribe later moved this crop during their expansion from Southern Cameroon region around first century AD, and the southern border of the Congo forest belt. The present-day sorghums of Central and Southern Africa bear close relationship with those of the Tanzania and are more distantly related to those of West African varieties, since the equatorial forests were an effective barrier to their spread (FAO 1995).

During the first millennium BC, sorghum was probably carried to India from Eastern Africa in ships as food by the chow traffic which operated for about

3000 years between East Africa (the Azanean Coast) and India via the Sebaean Lane in Southern Arabia. The sorghum varieties of India bear relationship to those existing in Northeastern Africa and the coast between Cape Guardafui and Mozambique. This crop might have spread along the coast of Southeast Asia and around China around the beginning of Christian era; however, a possibility that cannot be denied is that sorghum might have arrived much earlier in China by the silk trade routes (FAO 1995). Later it made its way to Western parts of the World via Asia. This plant was mentioned in European botanical literature in 1542 and was referred to as Sorghi, the name similar to that used in India.

Sorghum was introduced in the Caribbean Islands and other Latin American countries from West Africa through the slave trade and by navigators plying the Europe-Africa-Latin America trade route in the early 17th century as another source for sugar production. The case is similar for Australia. These early varieties were established as “guinea corn” (also called as Rural Branching Durra). However, the guinea corn in course of time disappeared from production. The tropical adapted varieties were introduced via slave trader ships as broomcorn variety by Benjamin Franklin in the United States in 1725, while Johnson grass was introduced as forage grass variety in South Carolina in 1830. These varieties were cultivated extensively in the US after 1850s, when sweet sorghum was introduced in 1853 by William Prince, a New York nurseryman who received some seed from France via China and cultivated the sorghum crop in New York. He claimed that sweet sorghum was a potential new sugar crop and sold the seed to farmers around Northern America for mass cultivation. In a parallel effort, J.D. Browne, a United States patent agent, traveled to France and noticed French efforts on sweet sorghum cultivation for sugar production from the sweet canes, which grew in places having similar climatic conditions favoring corn cultivation. Based on these observations, Browne collected seed from France and sent them back to the US Patent office and advised that this crop can act as a new sugar source and could be cultivated in America’s Corn Belt like American North and Midwest regions.

The sweet sorghum varieties introduced by William Prince and J.D. Browne were termed as “Black amber” or “Chinese sugarcane” since they arrived in America though France via China. The Chinese sugar cane variety was also known as Eusorghum. Since then many sweet and forage varieties were introduced in the US from China, Africa and Australia and were domesticated (Vinall et al. 1936; Ziggers 2006). Subsequently, sorghum production was established in the United States to a larger extent with the introduction of grain sorghum variety in California in 1874 and the milo variety’s introduction by the Colombian missionary H.B. Pratt in 1879. In the early 1900s, grain sorghum was identified as a drought-tolerant crop and its production surpassed corn in the arid regions of the Southern Great Plains. Scientists from various agricultural experiment stations and USDA scientists from Texas, Oklahoma and Kansas recorded the sorghum’s drought tolerance and with the help of seed production farmers selected improved phenotypes. Many local land laces of sweet stalked sorghum found in Western and Central Africa (Mali, Niger and Tanzania) are used for staple purpose.

3 Sweet Sorghum and its Utilization

Characteristics: The term sweet sorghum is used to distinguish varieties of sorghum with high concentrations of soluble sugars in the plant stalk sap or juice compared to grain sorghum which has relatively less sugar and juice in the stalks. Sweet sorghum is a C_4 plant species having wide flat leaves and a round or elliptical head with full of grain at the stage of maturity. It is, like grain sorghum, traditionally under cultivation for nearly 3000 years. It can be grown successfully in semi-arid tropics, where other crops fail to thrive and are highly suitable for cultivation in harsh dryland growing areas. With irrigation, it can produce very high yields. During very dry periods, sweet sorghum can go into dormancy, with growth resuming when sufficient moisture levels return (Gnansounou et al. 2005). It can be grown easily on all continents, in tropical, sub-tropical, temperate, semi-arid regions as well as in poor quality soils. It is known as the sugarcane of the desert and also "the camel among crops" for its drought hardy characteristics (Sanderson et al. 1992). It has higher drought tolerance and water use efficiency (WUE) compared to maize, and yields, like those of *Miscanthus*, ranging from 18 to 36 dry t ha^{-1} of biomass per year on low-quality soils with minimal inputs of fertilizer and water. In Indiana, studies showed that sweet sorghum cultivars produced 25–40 tons of dry mass per hectare with 0–60 kg ha^{-1} of nitrogen fertilizer. The high WUE and low N requirements of sorghum also provide significant advantages to the growers, because sorghum fits into a normal rotation scheme with corn and soybeans, yet has lower production costs and employs similar production equipment. Its ratooning ability enables multiple harvests per season, a feature that could expand the geographical range of sorghum cultivation. The grain, stalk juice and bagasse (the fibrous residue that remains after juice extraction) can be used to produce food, fodder, ethanol and power. Owing to these favorable attributes, William D Dar, refers to it as a **SMART** crop (Fig. 1). It's candidate traits *vis-a-vis* utilizable options are listed in Table 1.

These important characteristics, along with its suitability for seed propagation, mechanized crop production, and comparable ethanol production capacity *vis-a-vis* sugarcane and sugarbeet makes sweet sorghum a viable alternative source for ethanol production (Table 2).

The sweet sorghum value chain basically involves four critical areas i.e. feed stock supply, sugars conversion, bioenergy (ethanol blended gasoline) distribution and use (Fig. 2). In a feedstock like sweet sorghum, whole plant, its products and byproducts are used for diverse purposes.

4 Sorghum Distribution and Climatic Conditions

Sorghum (*Sorghum bicolor* (L) Moench) is the fifth important cereal crop in the world in production and fifth in acreage after wheat, rice, maize and barley. It is mostly grown in the semi-arid tropics (SAT) of the world wherein the production

Fig. 1 An ICRISAT improved sweet sorghum variety, ICSV 25274

system is constrained by poor soils, low and erratic rainfall and low inputs resulting in low productivity. In terms of area, India (7.5 m ha) is the largest sorghum grower in the world followed by Nigeria (7.6 m ha) and Sudan (6.6 m ha). India is the third largest producer after USA and Nigeria. Sorghum is well adapted to the SAT and is one of the most efficient dryland crops to convert atmospheric CO_2 into sugar (Srinivasa Rao et al. 2009). The crop can be grown in a wide range of climatic conditions as given below.

Latitude: Sorghum is grown between 45°N and 45°S latitude on either side of the equator.

Altitude: Sorghum can be found at elevations between mean sea level and 1,500 m. Most East African sorghum is grown between the altitudes of 900–1,500 m, and cold-tolerant varieties are grown between 1,600 and 2,500 m in Mexico.

Temperature: Sweet sorghum can be grown in the temperature range of 12–37 °C and optimum temperature for growth and photosynthesis is 32–34 °C, day length is 10–14 h, optimum rainfall ranges from 550 to 800 mm and relative humidity ranges between 15 to 50 %.

Soils: Alfisols (red) or vertisols (black clay loamy) with pH ranging between 6.5 to 7.5, organic matter >0.6 %, depth >80 cm, bulk density <1.4 gcc, water holding capacity >50 % field capacity, N $\geq$ 260 kg ha^{-1} (available), P $\geq$ 12 kg ha^{-1} (available), K $\geq$ 120 kg ha^{-1} (available).

Water: Sorghum will survive with a supply of less than 300 mm over the season of 100 days, while it responds favorably with additional rainfall or

Table 1 Candidate traits of sweet sorghum as biofuel feedstock (Reddy et al. 2005; Srinivasa rao et al. 2009, 2010)

As crop	As ethanol source	As bagasse	As raw material for industrial products
Short duration (3–4 months)	Amenable to eco-friendly processing	High biological value	Cost-effective source of pulp for paper making
C_4 dryland crop Good tolerance of biotic and abiotic constraints	Less sulphur in ethanol High octane rating	Rich in micronutrients Use as feed, for power co-generation or bio-compost	Dry ice, acetic acid, fusel oil and methane can be produced from the co-products of fermentation
Meets fodder and food needs Non-invasive species Low soil N_2O and CO_2 emission Seed propagated	Automobile friendly (up to 25 % of ethanol-petrol mixture without engine modification)	Good for silage making	Butanol, lactic acid, acetic acid and beverages can be manufactured

irrigation water. Typically, sweet sorghum needs between 500 to 1000 mm of water (rain and/or irrigation) to achieve good yields, i.e., 50–100 t ha^{-1} total above ground biomass (fresh weight). Though sorghum is a dryland crop, sufficient moisture availability for plant growth is critically important for high yields. The major advantage of sorghum is that it can become dormant especially in vegetative phase under adverse conditions and can resume growth after relatively severe drought. Early drought stops growth before panicle initiation and the plant remains vegetative; it will resume leaf production and flower when conditions again become favorable for growth. Mid-season drought stops leaf development. Sorghum is susceptible to sustained flooding, but will survive temporary water logging much better than maize.

Radiation: Being a C_4-plant, sweet sorghum has high radiation use efficiency (RUE, about 1.3–1.7 g M J^{-1}). It has been shown that taller sorghum types possess higher RUE, because of a better light penetration in the leaf canopy.

Photoperiodism: Most hybrids of sweet sorghum are relatively less photoperiod-sensitive. Traditional farmers, particularly in West Africa, use photoperiod-sensitive varieties. With photoperiod-sensitive types, flowering and grain maturity occur almost during the same calendar days regardless of planting date, so that even with delayed sowing, plants mature before soil moisture is depleted at the end of the season.

5 Taxonomy

The name *Sorghum bicolor* (L.) Moench was proposed by Clayton in 1961 as the correct name for the cultivated sorghum which is currently in use (Spangler 2003). The genus *Sorghum* is a variable complex genus belonging to the tribe

Table 2 Comparison of sweet sorghum with other bioethanol feedstocks (Reddy et al. 2008; Srinivasa Rao et al. 2009; Almodares and Hadi 2009; Wortmann et al. 2010; Girase 2010)

Characteristics	Sugarcane	Sugar beet	Corn	Sweet sorghum
Crop duration (months)	12–13	5–6	3–4	4
Growing season	One season	One season	All seasons	All seasons (if water is available)
Propagation	Seed (40,000 ha^{-1})	Seed (3.6 kg ha^{-1}; pellet)	Seed (25 kg ha^{-1})	Seed (8 kg ha^{-1})
Soil requirement	Grows well in drained soil	Grows well in sandy loam; also tolerates alkalinity		All types of drained soil
Water management	Requires water throughout the year (36,000 m^3 ha^{-1})	Requires water, 40–60 % compared to sugarcane (18,500 m^3 ha^{-1})	Requires water (12,000 m^3 ha^{-1})	Less water requirement; can be grown as rain-fed crop (8,000 m^3 ha^{-1})
Crop management	Requires good management 250 to 400 N 125P-125 K	Requires moderate management 120 N-60P-60 K	Requires good management 130 N-60P-60 K	Easy management; low fertilizer 90 N-40 P
Stalk/beet/grain yield (t ha^{-1})	60–85	85–100	5–10	45–65
Sugar content on weight basis	10–12 %	15–18 %		7–12 %
Sugar yield (t ha^{-1})	5–12	11.25–18		3–7
Ethanol yield from juice (l ha^{-1})	4,350–7,000	7,100–10,500	2,150–4,300	2,475–3,500
Harvesting	Harvested mechanically	Harvested mechanically	Harvested mechanically	Very simple; Predominantly manual and mechanical harvesting at pilot scale

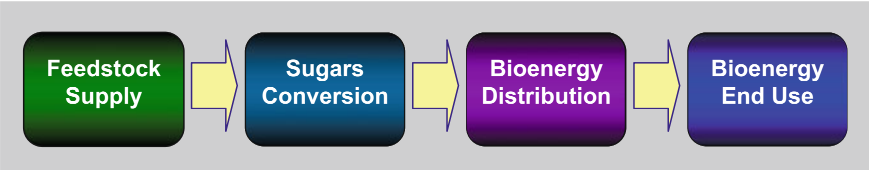

Fig. 2 Critical areas in sweet sorghum ethanol value chain (Srinivasa Rao et al. 2009)

Andropogoneae of the grass family Poaceae, which comprises of 24 species with various chromosome numbers and are subdivided into five sub-generic sections based upon node, panicle and spikelet morphology: Eu-sorghum (Stapf), Chaeto-sorghum, Heterosorghum, Para-sorghum (Snowden) and Stiposorghum (Garber 1950; de Wet 1978; Lazarides et al. 1991; USDA-ARS 2006). Section Eu-sorghum has six species consisting of cultivated, proginetor and weed species such as *Sorghum bicolor, S. arundinaceum, S. drummondii, S. halepense, S. propinquum* and *S. almum*, that have their natural range spread throughout Africa and Asia (de Wet 1978; Duvall and Doebley 1990). The other *Sorghum* species within the section Eu-sorghum forms the secondary gene pool and breeders have accessed genes from these species by introgression. The rest nineteen *Sorghum* species belonging to sub-generic sections other than Eu-sorghum formed the untapped tertiary gene pool. They are distributed primarily in Africa, Asia, Australia and South America, consisting of the cultivated species, their progenitors, and some serious weed species, and have close genetic relationships and inter-crossabilities (de Wet and Harlan 1971; Doggett 1976). *Sorghum bicolor* is a perennial diploid ($2n = 20$), which further includes three subspecies, namely, *S. bicolor* (cultivated sorghum) and its nearest wild relatives, *S. arundinaceum* (Desv.) de Wet et Harlan (wild sorghums) and *S. drumondii* (Steud.) de Wet (weedy sorghums). Subspecies *bicolor* includes all cultivated races and they are further subdivided into basic and intermediate races. The five basic races include *bicolor, guinea, caudatum, kafir* and *durra* and the ten intermediate races are those between any two of those types, classified primarily based on grain shape, glumes and panicle (Harlan and de Wet 1972).

6 Reproductive Biology

Sorghum is considered as a predominantly self-pollinated species but with cross pollination occurring to an extent of 4–10 % under specific conditions.

Panicle initiation: Sorghum is a short day plant, and blooming is hastened by short days and long nights. However, varieties differ in their photoperiod sensitivity (Quinby and Karper 1947). Tropical sweet sorghum varieties initiate the reproductive stage when day lengths return to 12 h. Floral initiation takes place 30–40 days after germination. Usually, the floral initial is 15–30 cm above the ground when the plants are about 50–75 cm tall (House 1980). Floral initiation marks the end of the vegetative growth due to meristematic activity. The time required for transformation from the vegetative apex to reproductive apex is largely influenced by genetic characteristics and the environment (photo-period and temperature). The grand period of growth in sorghum follows the formation of a floral bud and consists largely of cell enlargement. Hybrids take less time to reach panicle initiation and are relatively less influenced by photo-period and temperature (Srinivasa Rao et al. 2009).

Panicle emergence: During the period of rapid cell elongation, floral initial develops into an inflorescence. About 6–10 days before flowering, the boot will form as a bulge in the sheath of the flag leaf. This will occur, in a variety that flowers in 60–65 days, about 55 days from germination. Sorghum usually flowers in 55 days to more than 70 days in warm climates, but flowering may range from 30 days to more than 100 days. These observations are valid for tropical sweet sorghums, while temperate sorghums that mature in 5 months or later take longer period by 20–30 days for panicle emergence.

Panicle structure: Inflorescence is a raceme, which consists of one or several spikelets. It may be short, compact, loose or open, composed of a central axis that bears whorls of primary branches on every node. The racemes vary in length according to the number of nodes and the length of the internodes. Each primary branch bears secondary branches, which in turn bear spikelets. The central axis of the panicle, the rachis, is completely hidden by the density of the panicle branches in some, while it is completely exposed in others. The spikelet usually occurs in pairs, one being sessile and the second borne on a short pedicel, except the terminal sessile spikelet, which is accompanied by two pediceled spikelets. On the pediceled spikelet, the pedicels vary in length from 0.5 to 3.0 mm, and usually are very similar to the internodes. The first and second glumes of every spikelet enclose two florets; the lower one is sterile and is represented by a lemma, and the upper fertile floret has a lemma and palea. Two lodicules are placed on either side of the ovary at its base. Androecium consists of one whorl of three stamens. The anthers are attached at the base of the ovule by a very fine filament and are versatile and yellowish in color. Gynoecium is centrally placed and consists of two pistils with one ovule from which two feathery stigmas protrude. Many of these floral characters, such as anther color, stigma color, stigma length, length of pedicel, etc. are important traits for cultivar identification and classification.

Sessile spikelets: The sessile spikelet contains a perfect flower. It varies in shape from lanceolate to almost rotund and ovate and is sometimes depressed in the middle. The color is green at flowering, which changes to different colors like straw, cream, yellow, red, brown, purple, or almost black at grain maturity. The intensity and extent of coloring on the glumes is variable. Glumes vary from quite hairy to almost hairless. The seed may be enclosed by the glume or may protrude from it, being just visible to almost completely exposed.

Pediceled spikelets: These are much narrower than the sessile spikelets, usually lanceolate in shape. They can be smaller, the same size, or longer than the sessile spikelets. They possess only anthers but occasionally have a rudimentary ovary and empty glumes.

Anthesis and pollination: Anthesis starts after panicle emergence. Flowers begin to open 2 days after full emergence of the panicle. Floret opening or anthesis is achieved by swelling of the lodicules, and is followed by the exertion of anthers on long filaments and of stigmas from between the lemma and palea. Sorghum head begins to flower at its tip and flowers successively downward over a 4 or 5 day period. Flowering takes place first in the sessile spikelets from top to bottom of the inflorescence. It takes about 6 days for completion of anthesis in the panicle with maximum flowering at 3 or 4 days after anthesis begins. Flowering proceeds downwards to the base in a horizontal plane on the panicle. When flowering of the sessile spikelets is halfway down the panicle, pedicellate spikelets start to open at the top of the panicle and proceed downwards. The flowering phase of pedicellate spikelets overtakes the flowering phase of sessile spikelets before they reach the base of the inflorescence (Maiti 1996). Anthesis takes place during the morning hours, and frequently occurs just before or just after sunrise, but may be delayed on cloudy damp mornings. It normally starts around midnight and proceeds up to 10:00 h depending on the cultivar, location and weather. Maximum flowering is observed between 6:00 and 8:00 h. Because all heads in a field do not flower at the same time, pollen is usually available for a period of 10–15 days. At the time of flowering, the glumes open and all the three anthers fall free, while the two stigmas protrude, each on a stiff style. The anthers dehisce when they are dry and pollen is blown into air. Pollen in the anthers remains alive for several hours after pollen shedding. Flowers remain open for 30–90 min. Dehiscence of the anthers for pollen diffusion takes place through the apical pore. The pollen drifts to the stigma, where it germinates; the pollen tube, with two nuclei, goes down the style, to fertilize the egg and form a 2n nucleus. Glumes close shortly after pollination, though the empty anthers and stigmas still protrude (except in the long-glumed types). The florets of some of the very long-glumed types do not open for fertilization—a phenomenon known as cleistogamy.

Cytoplasmic male sterility has been found in sorghum (A_1–A_4 systems) and has made possible the development of a hybrid seed industry. A good male-sterile plant will not develop anthers, but in some instances dark-colored shriveled anthers with no viable pollen will appear. Partially fertile heads are also observed, and although the anthers frequently have viable pollen, the quantity is less than in normal plants.

Seed: The ovule begins to develop as a light green, almost cream-colored sphere; after about 10 days it begins to take size and becomes darker green. Maturity of grain follows a similar pattern to that of flowering. The development of grains follows a sequence of stages comprising milky, soft dough, hard dough to the final physiological maturity, when a black layer is formed at the hilar region due to the formation of callus tissue. It takes about 30 days for the seeds to reach maximum dry weight (physiological maturity). The seeds contain about 30 % moisture at physiological maturity; they dry to about 10–15 % moisture during the following 20–25 days (House 1980). The seed can be harvested at any time from physiological maturity to seed dryness; however, seed with more than 12 % moisture must be dried before storage. The seeds harvested and dried at physiological maturity have good quality and fetches higher market price (Audilakshmi et al. 2005). There is a distinct varietal difference in the rate of senescence of remaining leaves. All leaves may be dried, or almost dried, at grain maturity; or the plant may remain green. Seed size varies from very small (less than 1 g/100 seeds) to large (5–6 g/100 seeds).

7 Food: Fuel Trade off

It is often stated that sweet sorghum cultivars do not produce grain yield or the grain yield is very less *vis-a-vis* grain sorghum. Studies at ICRISAT showed that sweet sorghum hybrids had higher stem sugar yield (11 %) and higher grain yield (5 %) as compared to grain sorghum types, while sweet sorghum varieties had 54 % higher sugar yield and 9 % lower grain yield as compared with non-sweet stalk varieties in the rainy season. On the other hand, both sweet sorghum hybrids and varieties had higher stalk sugar yields (50 and 89 %) and lower grain yields (25 and 2 %) in the post-rainy season. Thus, there is little tradeoff between grain and stalk sugar yields in the sweet sorghum hybrids in the rainy season, while the trade off is less in varieties in the post-rainy season (Srinivasa rao et al. 2009, 2010; Kumar et al. 2010). The experimental data on the relationship between stalk sugar traits and grain yield shows that the regression coefficient of stalk sugar yield on grain yield is not significant; thereby indicating that the grain yield is not affected when selection is done for stalk sugar yield. Hence selection programs can aim to improve both the traits simultaneously.

8 Crop Agronomy

The already standardized agronomic practices for grain sorghum are not entirely applicable to sweet sorghum because sweet sorghums produce more biomass along with sugars. Developing improved eco-region specific agro-technology and pre- and post-harvesting stalk juice quality studies are the urgent priority. Moreover, the commercial viability of industry hinges upon raw material (sweet sorghum) availability for most part of the year. The adaptation (general and specific) of improved cultivars to different regions and seasons needs to be identified owing to high GGE interaction of sugar yield (Srinivasa Rao et al. 2011a) and its competent traits as described earlier. Standardization of optimized spacing (45 × 15 cm/ 60 × 15 cm/75 × 15 cm), fertilizer application (80–100 kg N, 30–50 P_2O_5), intercultural operations (thinning, weeding, soil mulch), irrigation schedule (both Alfisols and Vertisols apart from seasons), harvest timing and methodology will greatly enhance the productivity of sweet sorghum. In some areas response to micronutrients (like B, Zn and S) in juice yield and quality was observed (Srinivasa Rao et al. 2011b). The crop, even if uptakes different amount of nitrogen, seems to be insensitive to the mineral nitrogen supply and also seems to have a great potentiality in semi-arid environment in terms of yield production (Cosentino et al. 2012). The grain and sugar yields are best in the rainy and summer seasons, whereas in the post-rainy season the grain yield is high, but with less stalk and sugar yield. However, the results from tropical and temperate crosses have resulted in development of few post-rainy season cultivars at ICRISAT. In Brazil, efforts are being made to grow sweet sorghum in a period where stalks are harvested before and after sugarcane season so as to extend the period of operation of distillery. The present day multi-feedstock distilleries can successfully run on a variety of feedstocks like sugarcane, sweet sorghum, cassava and sugarbeet, etc. Agronomic and physiological measures aiding in increasing the period of industrial utilization (PIU) of sweet sorghum (e.g., customized fertilizer application, irrigation at physiological maturity, spraying gibberelic acid (GA), ethrel, solubar, etc., or soil application of micronutrients or other amendments to delay maturity, etc.) will further strengthen the use of sweet sorghum as a biofuel/industrial crop. Rapid sugar accumulation immediately after flowering and its retention for a longer period for staggered feedstock supply is another area of research that deserves immediate attention.

9 R & D Efforts

The USA varieties such as Keller, BJ248, Rio and Wray are some of the popular sweet sorghum varieties grown in the Americas, Europe, China and Thailand. Considerable progress has been made in breeding for improved sweet sorghum lines with higher millable cane and juice yields in India, China, Brazil and several other countries. The Sorghum Institute, Liaoning Academy of Agricultural Sciences has successfully bred and released new sweet sorghum hybrids Liaosiza No.1 in 1989 and Liaosiza No.2 in 1995, which are widely grown throughout China. Similarly in Brazil, Embrapa has released sweet sorghum cultivars like BR501, BR503 BR505, BRS506 BR507 and BRS601 for large scale cultivation (Schaffert personal communication). Dale, Theis, Cowley, Tracey, BJ 248 and Sugardrip are some of the other sweet sorghum varieties grown all over the world.

Sweet sorghum research at ICRISAT was initiated in 1980 to identify lines with high stalk-sugar content in part of the sorghum world germplasm collection maintained at ICRISAT's gene bank initially by chewing the stalks at maturity. Seventy accessions that tasted sweet were evaluated during the rainy season of 1980 and nine accessions with high Brix% were planted again in 1981 rainy season, of which two cultivars, IS-6872 and IS-6896, were selected. The mean Brix% of the nine accessions grown in 1980 and 1981 varied by only about 3 % between the two seasons, indicating that the differences between growing seasons had little influence on the stalk-sugar content. Apart from this, several sweet sorghum lines with high Brix% values were identified among Nigerian lines, Zimbabwe lines, and advanced breeding progenies at ICRISAT-Patancheru. Due to changed focus driven by donor perceptions and National Agricultural Research Systems (NARS) needs, sweet sorghum research at ICRISAT was discontinued in late 1990's. However, ICRISAT renewed its sweet sorghum research to contribute its share to meet the increased demand created for ethanol following the Indian Government's policy to blend petrol and diesel with ethanol and initiate a program for the identification/development of sweet-stalked and high biomass sorghum hybrid parents and varieties during 2002. In an effort to identify promising sweet stalk hybrid parents from the existing diverse set of grain sorghum hybrid parents at ICRISAT, as a short term strategy for immediate utilization for hybrid cultivar development, several B-lines, R-lines and varieties were evaluated for stalk sugar content over the seasons and years. As many as 30 A/B-lines and 35 R-lines/varieties were found to be better combiners for agronomic and sugar yield related traits. The breeding strategy of ICRISAT revolves around developing hybrid parental lines particularly in partnership with NARS partners. Apart from the above, 27 B-lines and 68 R-lines for rainy season adaptation and 19 B-lines and 35 R-lines for post-rainy season adaptation are in the pipeline. The hybrid cultivar, CSH 22SS, developed and released in India by Indian National Program, had the female parent from ICRISAT. The ICRISAT variety, ICSV 93046, was tested in All India Coordinated Sorghum Improvement Project (AICSIP), Hyderabad from 2005 to 2007 and was found superior to the control varieties (SSV 84 and CSV 19SS) and recommended for identification. Other promising lines from ICRISAT in AICSIP over last 2 years are: ICSV 25274 and ICSSH 58 in India. In 2011, CSV 24SS another sweet sorghum variety bred by Directorate for Sorghum Research (DSR), Hyderabad was released for cultivation. Thousands of hybrids and segregating populations are under evaluation for stalk sugar traits. Research experience at ICRISAT and elsewhere has showed that hybrids produce relatively higher biomass, besides being earlier and more photo-insensitive when compared to the varieties grown under normal as well as abiotic stresses including water-limited environments. The requirement of photo- and thermo-insensitiveness is essential to facilitate plantings at different dates for continuous supply of stalks to distilleries for ethanol production. Therefore, the development of sweet sorghum hybrids is receiving high priority to produce more feedstock and grain yield per drop of water and unit of energy invested.

Increased demand for food triggered by the fast-growing human population, the need to sustain biodiversity, and the spurt in investments in agricultural research by private sector have resulted in seeking the Intellectual Property Rights (IPR) for the valuable research products. This has led to the introduction of plant variety protection legislations across the world particularly in European countries and in the USA. International efforts to harmonize the IPRs across countries to improve trade led to holding of various conventions [including Union Pour la Protection des Obtentions Végétales (UPOV) 1991], leading to the establishment of guidelines on Plant Breeder's Rights (PBRs). This was followed by Uruguay round of deliberations, resulting in Trade Related Intellectual Property (TRIPs) rights in 1995.

The Article 27.3 (b) of TRIPs agreement makes it mandatory for the member countries to provide protection for plant varieties either by patents, by an effective *sui-generis* system, or any combination thereof for effective protection of intellectual property. The Government of India enacted a Protection of Plant Varieties and Farmers Rights Act (PPVFRA) during 2001, and consequently a National Plant Authority is established to facilitate the registration of plant varieties. The guidelines of PPVFRA are used for characterization and registration of newly bred cultivars. Hence, this book attempts the detailed characterization of sweet sorghum cultivars and female hybrid parents following the guidelines of PPVFRA in order to help the researchers, entrepreneurs, farmers and other stakeholders to identify the available sweet sorghum cultivars and understand their yield potential in tropics.

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