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REVIEW ARTICLE

Sweet Sorghum Research and Development in India: Status and Prospects

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Abstract Renewable energy is a critical source of energy that contributes to energy security, reducing dependence on fossil fuels and emission of greenhouse gases. India would require more than 6.3 billion liters of ethanol to meet its ambitious target of 20 % EBP by 2017. Sweet sorghum is a promising dryland adapted biofuel feedstock that addresses food-versus-fuel issue favourably. Owing to its genetic variability in terms of stalk sugar traits such as total soluble sugars, green stalk yield, juice quantity and grain yield various research institutes in India and abroad have developed superior varieties and hybrids. Two commercial sweet sorghum based distilleries were established in India but could not operate for long for several reasons. The decentralized crushing units were established to overcome the issues encountered by centralized units. The large scale cultivation of sweet sorghum can happen if improved cultivars with higher sugar yield with multiple biotic and abiotic stress tolerance are available besides more importantly the policy support from Government of India in terms of both producer and processor incentives materialize.

Keywords Sweet sorghum · Biofuel · Feedstock · Commercialization · Cultivation · Improvement

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Introduction

India is one of the fastest growing economies in the world and energy security is critical for its socio-economic development. India's energy security would remain vulnerable until alternative fuels to substitute/supplement petro-based fuels are developed based on indigenously produced renewable feedstocks. In biofuels, the country has a ray of hope in providing energy security. Biofuels are environment friendly fuels and their utilization would address global concerns about containment of carbon emissions. The transportation sector has been identified as a major polluting sector. Use of biofuels has, therefore, become compelling in view of the tightening automotive vehicle emission standards to curb air pollution. Since biofuels can be produced from a diverse set of crops, each country is adopting a strategy that exploits the comparative advantages it holds with respect to such crops. For example, sugarcane and maize are the main feedstock for ethanol in Brazil and US respectively, while rapeseed in Europe and palm oil in Malaysia are the main feedstocks for biodiesel (Reddy et al. 2005; Srinivasarao et al. 2009, 2010; Zhang et al. 2010). Sweet sorghum is being widely considered to be suitable biofuel feedstock to a tropical country like India as sugarcane is grown primarily for sugar while corn is used in food and poultry industry (Zhang et al. 2010).

National Biofuel Policy

The Government of India (GOI) approved the National Policy on Biofuels on December 24, 2009. The policy encourages use of renewable energy resources as alternate fuel to supplement transport fuels and had proposed an indicative target to replace 20 % of petroleum fuel consumption with biofuels (bioethanol and biodiesel) by end of 12th Five-Year Plan (2017). In a bid to renew its focus and strongly implement the Ethanol Blending Program (EBP), the Cabinet Committee of Economic Affairs (CCEA) on November 22, 2012, recommended 5 percent mandatory blending of ethanol with gasoline (GAIN report 2013). The government's current target of 5 % blending of ethanol in gasoline has been partially successful in years of surplus sugar production and unfilled when sugar production declines. The interim (ad-hoc) price of Rs 27 per liter would no longer hold as price would now be decided by market forces. According to CCEA, the EBP is presently being implemented in a total of 13 states with blending level of about 2 %. After accounting for domestic consumption, the net ethanol availability seems adequate to meet 2.9 and 2.1 % of ethanol blending target for 2013 and 2014, respectively. Presently, the contracted ethanol supply for calendar year 2013 is sufficient to meet 2.9 % blending target. It is estimated that by end of 2017, India would require more than 6.3 billion liters of ethanol to meet its ambitious target of 20 % EBP. Given the current pace of development, a target to meet 5 % blending of ethanol (1.6 billion liters) with gasoline looks plausible. Sweet sorghum is one of the first generation biofuel feedstock besides sugarcane, sugarbeet and cassava as in the National Biofuel Policy (2009) of GOI.

What is Sweet Sorghum?

Sweet sorghum, similar to grain sorghum except for its juice-rich sweet stalk, is being grown in USA (for syrup) and Africa (for fodder) since many centuries and is considered to be a potential bioethanol feedstock, expected to meet food, feed, fodder, fuel and fiber demands. Some sweet sorghum lines attain juice yields of 78 % of total plant biomass, containing 15–23 % soluble fermentable sugar (Srinivasarao et al. 2009). The sugar is composed mainly of sucrose (70–80 %), fructose, and glucose. Most of the sugars are uniformly distributed in the stalk, with about 2 % in the leaves and inflorescences (Vietor and Miller 1990), making the crop particularly amenable to direct fermentable sugar extraction. Sweet sorghum is a C_4 species plant 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 3,000 years. It can be grown successfully in semi-arid tropics, where other crops fail to thrive and are highly suitable for cultivation in tougher dryland growing areas. It can produce very high yields with irrigation. 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. It has higher drought tolerance and water use efficiency (WUE) compared to maize, and yields, like those of *Miscanthus*, range 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 show that sweet sorghum cultivars produce 25–40 tons of dry mass per hectare with 0–60 kg ha^{-1} of nitrogen fertilizers. 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 (Srinivasarao et al. 2011). Its ratooning ability enables multiple harvests per season, a feature that could expand the geographical range of sorghum cultivation. For example, in Nebraska, cold-tolerant sweet sorghum planted in April yielded 22 t ha^{-1} of dry biomass, and a ratoon crop harvested from the same material in mid-October gave an additional 12 t ha^{-1} (Ali et al. 2008). The grain stalk juice and bagasse (the fibrous residue that remains after juice extraction) can be used to produce food, fodder, ethanol and power. It's candidate traits *vis a vis* utilizable options are listed in Table 1. Further the lignocellulosic ethanol realization from sweet sorghum is relatively higher vis avis other types of sorghums (Dien et al. 2009).

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).

It is often stated that sweet sorghum cultivars do not produce grain yield or the grain yield is very less *vis a vis* that of grain sorghum. Studies at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) showed that sweet sorghum hybrids had higher stem sugar yield (11 %) and higher grain yield (5 %) compared to grain sorghum types, while sweet sorghum varieties had 54 % higher sugar yield and 9 % lower grain yield compared to 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 (Reddy et al. 2012). Thus, there is little tradeoff between grain and stalk sugar yields in the sweet sorghum hybrids in the rainy season while the tradeoff is less in varieties in the post-rainy season (Srinivasarao et al. 2009, 2010; Kumar et al. 2010).

This is further supported by other published work (Zhao et al. 2009) showing that there is significant soluble sugars

Table 1 Candidate traits of sweet sorghum as biofuel feedstock

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	Less sulphur in ethanol	Rich in micronutrients	Dry ice, acetic acid, fusel oil and methane can be produced from the co-products of fermentation
Good tolerance of biotic and abiotic constraints	High octane rating	Use as feed, for power co-generation or bio-compost	Butanol, lactic acid, acetic acid and beverages can be manufactured
Meets fodder and food needs	Automobile friendly (up to 25 % of ethanol-petrol mixture without engine modification)	Good for silage making	
Non-invasive species			
Low soil N_2O and CO_2 emission			
Seed propagated			

Source Reddy et al. 2010 and Srinivasarao et al. 2009, 2010

Table 2 Comparison of sweet sorghum with other bioethanol feedstocks

Characteristics	Sugarcane	Sugar beet	Corn	Sweet sorghum
Crop duration	12–13 months	5–6 months	3–4 month	4 months
Growing season	One season	One season	All seasons	All seasons (if water is available)
Propagation soil requirement	Setts (40,000 ha^{-1}) grows well in drain soil	Seed (3.6 kg ha^{-1}; pellet) grows well in sandy loam; also tolerates alkalinity	Seed (25 kg ha^{-1})	Seed (8 kg ha^{-1}) 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–125 P–125 K	Requires moderate management 120 N–60 P–60 K	requires good management 130 N–60 P–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

Source Reddy et al. 2005, Srinivasarao et al. 2009, Almodares and Hadi 2009, Wortmann et al. 2010 and Girase 2010

content in the stems (79–94 %) during post-anthesis period, with the hybrids exhibiting significantly high soluble sugar content over varieties with same maturity period, effects of year, harvest time and genotype on calculated ethanol yield (CEY) are highly significant. 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 a selection program can aim to improve both the traits simultaneously. Sweet sorghum is a solution to the food-versus-fuel issue.

Sweet sorghum experiences a short vegetative period at a very high photosynthetic rate, hence, can produce more sugar than any other crop. It experiences little disease or pest attacks, and produces good cash flow at a low investment per acre. Shifts in production and use are occurring currently due to rapid expansion of ethanol distilleries in USA as evidenced by a 19 % increase in sorghum acreage in 2007 as compared to 2006 (NASS 2007).

Research and Development Efforts at ICRISAT

ICRISAT launched a global BioPower initiative in 2007 to find ways to empower the dryland poor to benefit from emerging opportunities in renewable energies. This involves the collaborative partnership of National Agricultural Research System (NARS), particularly India, the Philippines, Mali and private sector partners in Brazil, USA, Germany and Mexico. ICRISAT focuses on hybrids parent development to produce cultivars withstanding biotic and abiotic stresses thereby strengthening sweet sorghum value chains and their impact. The ICRISAT has made the first attempt in India to evaluate and identify useful high biomass producing sweet sorghum germplasm from world collections. The sweet sorghum program at ICRISAT primarily focuses on developing primarily hybrid parents adapted to rainy and postrainy seasons due to the highly significant interaction of genotype by environment (G × E). However about 100 sweet sorghum varieties/restorer lines and 50 improved hybrids were identified (Srinivasarao et al. 2013b). ICSV 93046, ICSV 25274, ICSV 25280 and ICSSH 58 were identified for release owing to their superior performance in All India Coordinated Sorghum Improvement Project (AICSIP) multilocation trials during 2008–2012 (Srinivasarao and Kumar 2013; Rao et al. 2012). Sweet sorghum improvement aims for simultaneous improvement of stalk sugar traits such as total soluble sugars or (Brix %), green stalk yield, juice quantity, girth of the stalk and grain yield. Conventional breeding approaches are practiced for an increase in sucrose yield; R lines showed a brix % of 12–24 % in the rainy season and 9–19 % in the postrainy season. 600 A/B pairs were screened at ICRISAT and the % brix ranged from 10 to 15 % in the rainy season and 8–13 % in the postrainy season (Srinivasarao et al. 2009). The bagasse of sweet sorghum is highly palatable and intake by livestock is more vis avis normal sorghum stover (Blümmel et al. 2009; Srinivasarao et al. 2012).

Some of the insect and pest resistant materials have developed at ICRISAT such as ICSR 93034 and ICSV 700. The first sweet sorghum hybrid released in India is CSH 22SS. ICSV 93046 (ICSV 700 × ICSV 708) is a promising shoot fly, stem borer and leaf diseases tolerant sweet sorghum variety also displays staygreen stems and leaves even after physiological maturity and has good grain (3.4–4.1 t ha^{-1}) and biomass yield. Another hybrid ICSSH 72 shows excellent fodder quality in rainy season and is resistant to leaf diseases. SPV 422 also exhibits resistance to leaf diseases and other hybrids developed at ICRISAT, India viz ICSSH 21 (ICSA 38 × NTJ 2) and ICSSH 58 (ICSA 731 × ICSV 93046) are under advance testing stages. ICSSH 30 variety shows superior grain yields in both rainy and post rainy seasons whereas ICSSH 39 and 28 are best for sugar yield. ICSSH 24 variety is supposed to be best suited for rainy season. Some of the varieties and hybrids developed from ICRISAT are given in Table 3.

Research and Development Efforts at NARS

Sweet sorghum research in India is carried out at Directorate of Sorghum Research (DSR), Hyderabad and at AICSIP centers like Parbhani, Rahuri, Phaltan, Akola (Maharashtra), Anakapalli, Perumallapalli, Hyderabad and Palem (Andhra Pradesh), Coimbatore (Tamil Nadu), Surat (Gujarat), Ludhiana (Punjab) and Pantnagar (Uttarkhand). The Lucknow based Indian Institute of Sugarcane Research (IISR), Punjab Agricultural University (PAU), Ludhiana; Govind Ballabh Pant University of Agriculture & Technology (GBPUAT) Pantanagar; Tamilnadu Agriculture University (TNAU), Coimbatore; Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri; Marathwada Agricultural University (MAU), Pharbhani and Dr. Panjabrao Deshmukh Krishi Vidyapeeth (PDKV), Akola are also conducting research on sweet sorghum. Nimbkar Agricultural Research Institute (NARI), Phaltan, Maharashtra has commercialized sweet sorghum derived syrup. At all India level, every year promising sweet sorghum entries which includes hybrids and varieties contributed by various centers are tested across locations against standard checks. During rainy 2012, twenty-three Initial-cum-Advanced Sweet Sorghum Varietal & Hybrid Trial (IASSVHT) entries comprising 16 varieties, 4 hybrids along with 3 checks (CSV 24SS, CSV 19SS and CSH 22 SS) were evaluated across 12 locations.SPH 1711 with a flowering of 73 days was significantly early and had 8 % superiority over the check hybrid (79 days). For total biomass, SPV 2196 was 11 % more yielding than CSV 24SS and 18 % significantly superior to CSV 19SS. It was also promising for fresh stalk yield too. For grain yield, none of the test hybrids were significantly superior to the check CSH 22SS. Among the test varieties, SPV 2199 recorded a superiority of 12 % over CSV 24SS. With respect to brix content, SPV 2198, SPV 2197, SPV 2135, SPV 2199 and SPV 2206 were promising. For juice yield, the hybrid SPH 1739 and varieties SPV 2196 and SPV 2200 exhibited significant

Table 3 Improved sweet sorghum varieties and hybrids developed from ICRISAT

Varieties			Hybrids	
ICSV 25263	ICSV 25303	ICSV 12006	ICSSH 1	ICSSH 41
ICSV 25264	ICSV 25304	ICSV 12007	ICSSH 2	ICSSH 42
ICSV 25265	ICSV 25305	ICSV 12008	ICSSH 3	ICSSH 43
ICSV 25266	ICSV 25306	ICSV 12009	ICSSH 4	ICSSH 44
ICSV 25267	ICSV 25307	ICSV 12010	ICSSH 5	ICSSH 45
ICSV 25268	ICSV 25308	ICSV 12011	ICSSH 6	ICSSH 46
ICSV 25269	ICSV 25309	ICSV 12012	ICSSH 7	ICSSH 47
ICSV 25270	ICSV 25310	ICSV 12013	ICSSH 8	ICSSH 48
ICSV 25271	ICSV 25311	ICSV 12014	ICSSH 9	ICSSH 49
ICSV 25272	ICSV 25312	ICSV 12015	ICSSH 10	ICSSH 50
ICSV 25273	ICSV 25313	ICSV 12016	ICSSH 11	ICSSH 51
ICSV 25274	ICSV 25314	ICSV 12017	ICSSH 12	ICSSH 52
ICSV 25275	ICSV 25315	ICSV 12018	ICSSH 13	ICSSH 53
ICSV 25276	ICSV 25316	ICSV 12019	ICSSH 14	ICSSH 54
ICSV 25277	ICSV 25317	ICSV 12020	ICSSH 15	ICSSH 55
ICSV 25278	ICSV 25318	ICSV 12021	ICSSH 16	ICSSH 56
ICSV 25279	ICSV 25319	ICSV 12022	ICSSH 17	ICSSH 57
ICSV 25280	ICSV 25320		ICSSH 18	ICSSH 58
ICSV 25281	ICSV 25321		ICSSH 19	ICSSH 59
ICSV 25282	ICSV 25322		ICSSH 20	ICSSH 60
ICSV 25283	ICSV 25323		ICSSH 21	ICSSH 61
ICSV 25284	ICSV 25324		ICSSH 22	ICSSH 62
ICSV 25285	ICSV 25325		ICSSH 23	ICSSH 63
ICSV 25286	ICSV 25326		ICSSH 24	ICSSH 64
ICSV 25287	ICSV 25327		ICSSH 25	ICSSH 65
ICSV 25288	ICSV 25328		ICSSH 26	ICSSH 66
ICSV 25289	ICSV 25329		ICSSH 27	ICSSH 67
ICSV 25290	ICSV 25330		ICSSH 28	ICSSH 68
ICSV 25291	ICSV 25331		ICSSH 29	ICSSH 69
ICSV 25292	ICSV 25332		ICSSH 30	ICSSH 70
ICSV 25293	ICSV 25333		ICSSH 31	ICSSH 71
ICSV 25294	ICSV 25334		ICSSH 32	ICSSH 72
ICSV 25295	ICSV 25335		ICSSH 33	ICSSH 73
ICSV 25296	ICSV 25336		ICSSH 34	ICSSH 74
ICSV 25297	ICSV 25337		ICSSH 35	ICSSH 75
ICSV 25298	ICSV 25338		ICSSH 36	ICSSH 76
ICSV 25299	ICSV 25339		ICSSH 37	
ICSV 25300	ICSV 25340		ICSSH 38	
ICSV 25301	ICSV 25341		ICSSH 39	
ICSV 25302			ICSSH 40	

superiority over respective checks. The hybrids SPH 1739 and SPH 1738 and varieties (SPV No‘s) 2196, 2200, 2202, 2197, 2074, 2241, 2201, 2205, 2195 and 2206 were promising for sugar yields and CEYs (Fig. 1) (AICSIP 2012).

Concerted research efforts at AICSIP centers have resulted in the identification of several promising sweet sorghum varieties such as SSV 96, GSSV 148, SR 350-3, SSV 74, HES 13, HES 4, SSV 119 and SSV 12611 for total soluble sugars (TSS) % and juice yield during 1991–1992 trials, GSSV 148 for cane sugar during 1993–1994 trials, NSS 104 and HES 4 for green cane yield, juice yield, juice extraction and total sugar content during 1999–2000 trials, and RSSV 48 for better alcohol yield during 2001–2002. An evaluation of 11 promising sweet sorghum varieties bred at different AICSIP centers indicated superiority of the

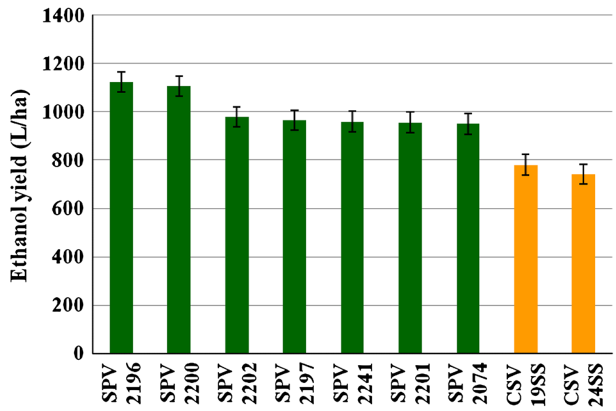

Fig. 1 Current levels of ethanol yields in promising varieties at Directorate of Sorghum Research

varieties, NSSV 255 and RSSV 56 for green cane yield, juice yield, juice extractability, commercial cane sugar (CCS) yield (q ha^{-1}) and percent non-reducing sugars over the rest of the varieties. The varieties RSSV 79, PKV809, NSSV 256 and NSSV 6 excelled the check with superior performance for green cane yield, juice yield, juice extractability, CCS yield and total sugars (Reddy et al. 2007).

The sweet sorghum improvement program during last two decades at DSR and AICSIP centers had resulted in development of a number of breeding lines, which led to release of several varieties such as SSV 84 (High Brix: 18 %), CSV 19SS (RSSV 9) and hybrid CSH 22 SS (NSSH 104) and the latest variety CSV 24SS (SPSSV 6) with productivity ranging from 40 to 50 t ha^{-1} (AICSIP 2004, 2005, 2006, 2007, 2008). In several multi-environment trials in India, SSV 84 has consistently yielded an average 37.5 t ha^{-1} of stalk yield with a stable brix (%) of 18.6. Assessment of sweet sorghum for post-harvest deterioration under ambient field condition revealed that stalk yield declined with increase in storage time with 12.0 % decrease at the end of 5 days (120 h). CSV 19SS recorded significantly higher stalk yield than CSV 24SS. Both mean TSS and reducing sugars (RS) increased significantly over control by the end of 4 days. Non-reducing sugars (sucrose content) decreased as storage time increased. The sucrose content recorded was almost similar until 48 h, while it decline by 25.8 % by the end of 72 h. These results suggest that the sugar content in the stalks and their weights can be retained up to 2–3 days after harvest in the ambient field storage conditions under the mild to moderate winter (November) semi-arid tropical climate.

Sweet Sorghum Cultivation and Experiences

It can be grown successfully in the semi-arid tropics, where other crop fail to thrive and this is highly suitable for cultivation in tougher dryland growing areas. It can be grown easily on all continents, in tropical, subtropical, temperate, semi-arid regions as well as in poor quality soils and low water requirement. It is a 4 month duration plant and can be cultivated 2–3 times a year and is tolerant to biotic and abiotic stresses such as drought, temperature and salinity. It can be grown as rain-fed crop (8,000 m^3 ha^{-1}). The following sections will discuss the different stakeholders who have cultivated sweet sorghum for various purposes

Traditional Use by Farmers

Traditionally sorghum for forage is grown under both rainfed and irrigated conditions. It is estimated that about 60–70 % of forage demand in rainy season is met from sorghum. In majority areas of sorghum cultivation in India sweet sorghum is cultivated in small pockets across different regions since time immemorial. For example the sweet sorghum variety “Amrutha” is grown in the villages around Rahuri, Ahmednagar district of Maharashtra. similarly farmers in Nandyal region of Andhra Pradesh where *magi* sorghum cultivation is predominant local sweet stalked sorghum land races were cultivated in large tracks few decades earlier until sorghum area declined due to competition from cotton and corn (Munirathnam et al. 2013).

Rusni Distillery

This was the first sweet sorghum distillery established in the year 2007 near Sangareddy, Medak district of Andhra Pradesh, India amenable to use multiple feedstocks for transport grade ethanol production. It generated 99.4 % of fuel ethanol with a total capacity of 40 kilo liters per day (KLPD). It also produced 96 % extra neutral alcohol (ENA) and 99.8 % pharma alcohol from agro based raw materials such as sweet sorghum stalks (juice), molded grains, broken ice, cassava and rotten fruits. ICRISAT has incubated sweet sorghum ethanol production in partnership with Rusni Distilleries through its Agri-Business Incubator. Rusni is a 40 KLPD ethanol production unit located in Medak district of Andhra Pradesh (approx. 25 km from ICRISAT headquarters). It is the world’s first sweet sorghum-based ethanol production distillery. It is a multi-feedstock unit and can use other feedstock, such as broken/damaged grain, cassava, sugarcane, cashew apple, and *mahua* in the lean season. Commercial ethanol production commenced at Rusni from June 2007. A distillery of Rusni’s capacity requires sweet sorghum stocks from 8,000 ha per year spread over different seasons, which comes to 3,500 ha in rainy season and 4,500 ha in the postrainy season. Rusni, with the help of Aakruthi

Agricultural Associates of India (AAI), organizes farmers for large-scale sweet sorghum cultivation on a 'buy-back' mode for stalk procurement (Srinivasarao and Kumar 2013). Issues encountered in the operation of the centralized model:

- The availability of sweet sorghum stalks for crushing is limited to two seasons and only available for a short period (30–45 days per season).
- The sweet sorghum stalks need to be crushed within 8–12 h of harvesting as sugars start inverting with time delay, which affects juice recovery and fermentable sugar content (Kumar et al. 2013). This limits the geographical command area of sweet sorghum crop cultivation within a periphery of 50 km radius of the distillery. The farmers beyond this area are not encouraged to take up sweet sorghum cultivation.
- As available days for crushing are limited, the entire crop of sweet sorghum stalks pile up at the distillery leading to wastage as the distillery cannot crush more than 900 t day^{-1}.
- Crop production is not mechanized to enable comparison of area; so there is no information available on juice quality, its stability and fermentation efficiency.

Tata Chemicals Limited (TCL)

This pilot scale sweet sorghum distillery of 30 KLPD capacity was established in 2009 at Nanded, Maharashtra. It used commercially grown sweet sorghum cultivars such as CSH 22SS, ICSV 93046, sugargrace, JK Recova and RSSV 9 in the 25 km radius of the distillery to produce transport grade ethanol and ENA during 2009–2010.

The forward linkages of the sweet sorghum farmers with TCL in distribution the timely inputs (seed, fertilizer) and technical information (crop agronomy and management) besides organization of on farm demonstrations/on-farm trials besides backward integration of feedstalk supply from farmers' fields to the distillery were shown in the (Figs. 2). ICRISAT played significant role in technical back dropping. In 2008 and 2009 the sweet stalk productivity levels were low. Hence a new novel contract farming model was followed in 2010 and it gave satisfactory results in enhancing farm productivity. The average productivity of sweet sorghum stalks (with leaves) was 8.25 tonnes per acre (20.6 t ha^{-1}) with net returns to farmer up to Rs. 24,325 ha^{-1}. The cultivars used were ICSV 93046, CSH 22SS and sugargrace with an average stalk productivity of 24.75, 24.75 and 31.2 t ha^{-1} respectively. Highest stalk yield was realized for ICSV 93046 at 53 t ha^{-1}.Raw material supply window was increased to 42 days and average returns to farmers ranged from Rs 15,000 to 20,000 comparable with competing crops like grain sorghum and soybean. Remarkable achievement in stalk productivity was observed by 33 % in the year 2010 with the partnership of TCL. CSH 22SS; late maturing sweet sorghum variety hybrid is highly popular in farmers because of its high stalk yields which was bred by DSR–ICRISAT (Srinivasarao et al. 2013a). Another centralized distillery "CF Biotech Ltd" is in the process of establishing multiple feedstock based distillery in Gadag district of Karnataka.

Nimbkar Agricultural Research Institute (NARI)

At NARI, Phaltan, initial attempts have been made to develop sweet sorghum by crossing indigenous germplasm with exotic ones that led to the identification of superior ones with high cane yield, high brix %, and moderate grain yield. Complete development of indigenous technology for fermentation of sweet sorghum juice, solar distillation of ethanol and finally its use as a cooking and lighting fuel in new and improved stoves and lanterns was carried out. The technology of producing jaggery (unrefined sugar) and syrup from sweet sorghum was also developed (Rajvanshi and Nimbkar 2001). Sweet sorghum syrup is being marketed under "Madhura" brand name. Sweet sorghum bagasse was also tested in an existing paper mill to assess its suitability for paper manufacture (NARI 2013). A total of 22 sweet sorghum accessions were tested for 3 years to identify the most promising ones for ethanol production. S 21-3-1 and S 23-1-1 were found to be the most promising in terms of stalk and grain yields, juice quality and total energy production per unit land area. The fermentation studies conducted at the Institute have shown that out of the 16 strains tested, the strain NCIM 3319 of yeast, *Saccharomyces cerevisiae* gave good results in batchwise fermentation of unsterilized juice to produce ethanol. Three hybrids, Madhura, NARI-SSH45 and NARI-SSH48 have been developed at NARI, all yield good grain and high brix sweet juice.

Decentralised Units

To overcome the problems in centralized model, it was envisaged a decentralized crushing unit (DCU) for syrup production to enhance the period of feedstock availability for ethanol production; to reduce the volume of feedstocks to be transported to the distillery, and to reduce the time lag between harvesting and crushing of stalks particularly when area of crop production is more than 50 km from the location of a centralized distillery. The DCU model (Fig. 3) will leave the bagasse at the village itself for use as animal feed and provide opportunities for local employment and entrepreneurship. ICRISAT and partners, with funding support from NAIP-ICAR established a DCU at

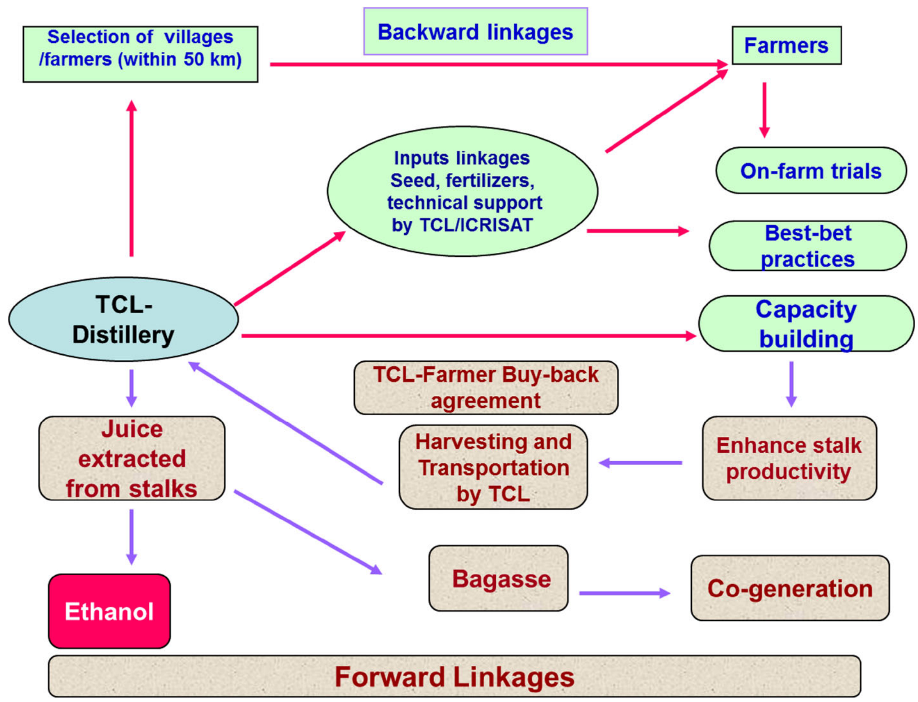

Fig. 2 Centralized model for linking farmers with distillery (TCL)

Ibrahimbad village in Medak district, AP. This is an initiative to assess the possibility of converting sweet sorghum juice to syrup which is storable for up to 1 year at room temperature without deterioration in sugars that would augment feedstock supply to the distillery for ethanol production, as and when required. This DCU was operated by farmers association during 2008–2012 with technical back dropping from ICRISAT, DSR, Central Research Institute for Dryland Agriculture (CRIDA) and AAI.

Similar DCU was established in Parbhani with the help of MAU under ICRISAT-CFC-FAO funded project in 2010 and it was operated during 2011–2012. The major constraints identified are.

(i) Lack demand for syrup as centralized distillery, TCL is not in operation
(ii) The uptake by food and pharma industry is limited.

Prospects

The uncertainty of fossil fuel supplies, ever increasing crude oil prices and the need to protect the environment is forcing several countries to look for renewable energy sources. Sweet sorghum cultivation on a commercial scale is yet to kick off in India and elsewhere. It is an ideal crop which can be grown in sugarcane growing areas to supplement molasses for ethanol production and also to use the existing sugarcane machinery in the off season. Approximately 4,000 sweet sorghum cultivars are distributed throughout the world (Grassi et al. 2004) indicating a diverse genetic background to develop regionally specific, highly productive cultivars (Bennett and Anex 2009).

The constraints for its large scale cultivation are the limited availability of genotypes suited to different agro-climatic conditions with all built-in resistances for biotic and abiotic stresses, photoperiod sensitivity and non-availability of required quantity of feedstock suited to off-season crushing in sugar industries. In order to meet the raw material demand of industry especially after sugarcane crushing, there is a need to develop sweet sorghum cultivars with all the desirable traits like high stalk yield per unit time, input, energy and land area in different agro-climatic areas of the country. These cultivars should also be photo-and thermo-insensitive with desired levels of resistance/tolerance to various kinds of stresses and should be of different maturities to widen the harvest window which thereby ensures a continuous supply of feed stock to the industry. Sweet sorghum parental line research needs urgent attention especially for enhancing genetic potential of females for high sugar content. Population improvement of sorghum provides long term breeding strategy to develop superior varieties and hybrid parents. While population improvement programs are not the most common in sorghum breeding, they are an important source of genetic variation and improved traits (Rooney and Smith 2000). Conversion of sorghum genotypes to adapt to long day conditions has increased genetic diversity and greatly contributed to improved grain crop quality and productivity

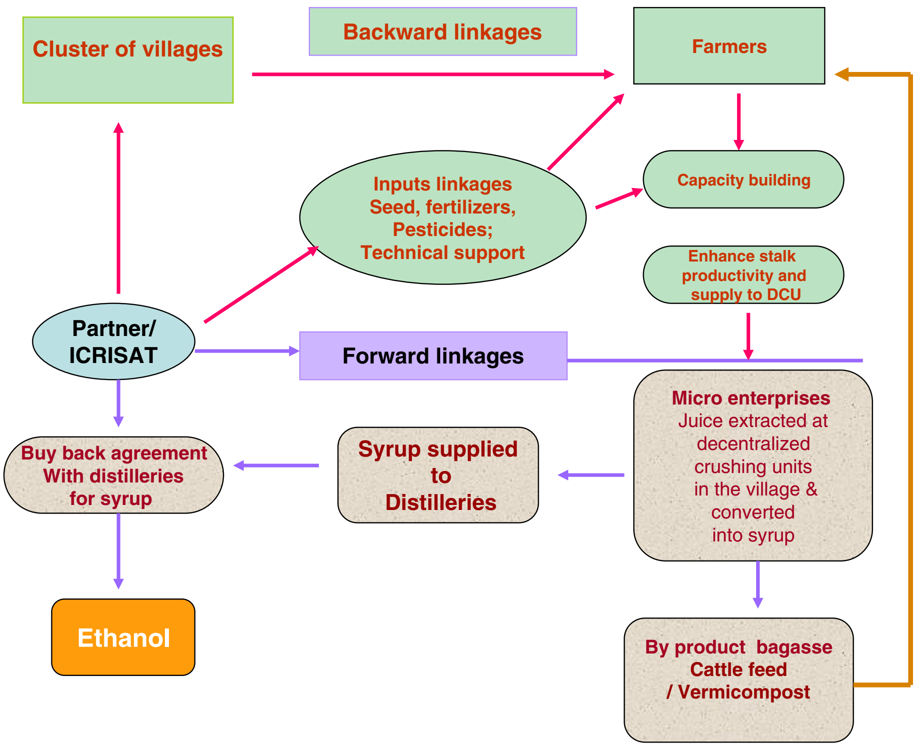

Fig. 3 Decentralized model—a village enterprise to crush stalks and produce syrup, linked with centralized model to produce ethanol from syrup

(Marguerat and Bahler 2010). The introduction of the brown midrib (*bmr*) trait in sweet sorghums would result in a dual-purpose bioenergy crop that supplies fermentable sugars from the stem juice, and from the enzymatic saccharification of the bagasse that remains after the juice has been collected. Development of *bmr* sweet sorghum as a dual source feedstock for ethanol production is emphasized in which the accumulation of soluble sugars in the stalk can be used for direct fermentation, and the remaining stover (residue) for the production of cellulosic ethanol (Vermerris et al. 2007; Srinivasarao et al. 2010).

There is a need to forge new collaborations with biofuel industries with the researchers and producers to make this novel multipurpose crop more remunerative. Through exploitation of sweet sorghum for food and as a source for ethanol production, its production would become attractive by linking farmers with new biofuel markets and consumers. Since ethanol is still under government control in India, there have to be basic policy changes before as it can be used for cooking and lighting. The following issues needs to be addressed on priority.

Processing Technology

The supply chain management (SCM) is the key to take this technology forward. For this viable and durable harvesting machinery for both grain and stalks is necessary to enhance benefit cost ratio of this value chain. In case of second generation (ligno-cellulosic) ethanol technology, research on feedstock improvement and processing aspects particularly on economizing the enzyme (cellulases) production costs should go hand in hand.

Adaptation to Postrainy Season

The jinx of low temperatures with lower sugar accumulation in sweet sorghum needs to broken so as to maximize sugar productivity in postrainy season.

Institutional Innovations for Value Chain Development

The decentralized model deals with production of raw materials through linking farmer groups with credit and input agencies and local crushing units i.e. DCUs who in turn are linked to the centralized distillery. The distilleries are linked to the association of distilleries, gas companies, and policy makers in concerned ministries of the government. Similar linkages will be established for by-products (bagasse) from the decentralized unit linking with electricity generators, livestock keepers etc. Through such a continuum and seamless integration of various actors at different stages of value chain (including by-products), benefits will be maximized from sweet sorghum for ethanol production.

Supply Chain Management and Capacity Building

Formulating a framework for command area development of sweet sorghum through corporate farming, contract farming, venture farming for industry linked with farmers associations either through centralized or decentralized model would go a long way in promoting the technology on a commercial basis. It is however, necessary to standardize and streamline the DCU model through optimization of operation and modalities with appropriate interventions from policy makers. Capacity building of the stakeholders on SCM of sweet sorghum from the farm to the industry on a regular basis.

Policy Support from Govt. of India

The ethanol support price is the deciding factor to give a fillip to this industry. A comprehensive study on the feedstock production and supply costs, processing and ethanol handling costs is needed to suggest minimum support price to be fixed by Govt. of India, as per the National Biofuel Policy 2009, so that the feedstock producers (farmers), distillers and the nation as whole is benefited. Government needs to evolve a national biofuel policy that addresses the issues of the entire stake holders of biofuel value chain (for example: incentives to farmers, local entrepreneurs, tax rebates to distilleries etc.).

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