Sweet sorghum: A Water Saving Bio-Energy Crop

Belum V S Reddy, A Ashok Kumar and S Ramesh
International Crops Research Institute for the Semi-Arid Tropics
Patancheru -502 324. Andhra Pradesh, India

The United Nations (UN) eight-millennium development goals (MDGs) provide a blueprint for improving livelihoods, and preserving natural resources and the environment with 2015 as target date. The UN member states and the world's leading development institutions agreed upon the MDGs. None of them however, have a specific reference to energy security considering that energy is the fuel of economic prosperity and hence assist to mitigating poverty. Nonetheless, diversification of the crop uses, identifying and introducing bio-fuel crops may lead to farmers' incomes, thereby contributing to *eradicating extreme poverty* (MDG 1) in rural areas helping 75% of the world's 2.5 billion poor (who live on <US$ 2 per day), and contributing to their energy needs. The energy is required for consumptive uses (cooking, lighting, heating, entertainment), for social needs (education and health care services), public transport (road, rail and air), industries, and agriculture and allied sectors. Agriculture practices in many developing countries continue to be based to a large extent on animal and human energy. Providing easy access to energy services (such as conventional fossil fuels renewable sources like solar, wind and bio-fuels) to the agriculture sector is essential to improve farm productivity and hence income of the peasants. However, access to fossil fuels is not a sustainable solution, as it will not provide social, economic and environment benefits considering very high price of fossil fuels and environment pollution associated with their use. The bio-fuels, produced from agriculture biomass among other renewable sources provide sustainable and eco-friendly energy options that foster *environmental sustainability* (MDG 7) and offer enormous opportunities to improve the level of developing world's smallholder subsistence farmers who depend on agriculture for their livelihoods (www.americanprogress.org). Last but not the least bio-fuel research-for-development may result from new global, regional, national and local public-private *partnerships for development* (MDG 8).

Energy and agriculture production

Modern agriculture requires energy inputs at all stages of production such as direct use of energy in farm machinery, irrigation management, and harvesting and indirect use for post harvest operations such as processing, storage and transport of commodities to markets. Empirical evidence suggests that the availability of modern energy sources such as fossil fuels were instrumental in increasing the agriculture productivity in industrialized countries. The difference between developing and industrialized countries in energy used per agriculture worker is dramatic with less than 5% of the total energy spent in developing countries compared to that spent (80%) in developed countries (www.fao.org). 'Energizing' the food production chain has been an essential feature of agriculture development to achieve food security. As in developed countries, there is also a strong correlation between per capita energy consumption and crop yields in developing countries. For example, in the Philippines, the productivity of rice (5.8 t ha^{-1}) grown using mechanized farming is far greater than that grown using traditional farming (1.2 t ha^{-1}) (www.fao.org). There is a strong correlation between energy consumption and gross national product, i.e., economic income which includes agricultural income also. The challenge for different countries, therefore, is energy security, especially transportation fuel security and hence the agricultural research orientation should aim to produce more biomass per drop of water and land in diversified cropping systems.

Bio-fuels and potential benefits

Bio-fuels (bio-ethanol and bio-diesel) produced from renewable energy sources are gaining importance in the light of rising fossil fuel prices, depleting oils reserves and increasing 'green house effect' associated with the use of fossil fuels. Several developing and developed countries have made a mix of policies to promote the production and use of bio-fuels. Ethanol accounts for 90% of total bio-fuels production and use in different parts of the world at present. The major feedstocks currently used for ethanol production are sugarcane molasses in Asia and Africa, sugarcane juice in Brazil, and corn in the USA. Ethanol production from these feed stocks suffers from two major problems – increased water use (sugarcane and corn), and pollution (all three feedstocks) compared to sweet sorghum. Sweet sorghum [*Sorghum bicolor* (L.) Moench] is well adapted to the Semi-Arid Tropics (SAT) and more water-use efficient (310 kg water/kg dry matter) compared to maize (370 kg water/kg dry matter) to convert atmospheric CO_2 into sugars which makes it the most promising bio-energy crop. The food, feed and fodder needs of smallholder farmers will not be affected as the 'juice' extracted from sweet sorghum stalks is used in ethanol production. The stillage leftover after the extraction of juice is an excellent dry matter source for livestock as it is rich in macro and micronutrients. The other sources of bio-fuels include cassava (*Manihot esculenta* Crantz) for ethanol and jatropha (*Jatropha curcas),* and pongamia *(Pongamia pinnata*) for biodiesel that are dry land crops and known to have high water use efficiency.

As bio-fuels are produced from biomass of crop plants, as indicated earlier, they offer enormous opportunities to improve the income levels of smallholder farmers in developing countries, which are predominantly agrarian economies. At community level, farmers can cultivate energy crops that fetch more income while meeting their food needs. Local production of bio-fuels is projected to have a broad range of positive economic, social and environmental implications. At a national level, producing more bio-fuels will generate new technologies, new industries, new jobs and new markets assisting economic growth in rural areas besides reducing environmental pollution. Of the 1.7 million jobs in 2004 related to the renewable energy industry, almost a million of them were related to bio-fuels. For example, in Brazil, the ratio of jobs created from bio-fuel industry to those created from fossil fuel industry is 22:1 at 100% ethanol use and 6:1 at 25% ethanol use in transport vehicles (www.americanprogress.org). Similarly, India's national mission on jatropha bio-diesel project is expected to generate employment to the tune of 16 million person days/year for the poor. The project also helps improve degraded land resources (http://www.jatrophabiodiesel.org/indianPrograms.php?_divid=menu5). Pongamia cultivation not only helps to produce bio-diesel, but also guarantee additional employment and improves soil fertility.

Current status of bio-fuel production

Bio-fuels are currently based on the generation of ethanol from sugars or starch derived from vegetative biomass or grain, or bio-diesel from the more direct use of edible and non-edible plant oils and animal fats (Ortiz et al. 2006). Brazil is the shining example for using ethanol (produced from sugarcane juice) either in pure form or as a blend with petrol (gasohol) for fuelling the automobiles. Billions of gallons of bio-ethanol are being produced in Brazil using sugarcane. Ethanol alone accounts for about 90% of total bio-fuel production (39 billion liters) in 2005 (www.commodityIndia.com) in the world. The gasohol (obtained by blending ethanol with petrol) is an environment-friendly fuel and its use is encouraged worldwide to reduce pollution as well as to reduce the fuel-import bills. Taking a cue from Brazil, several developed and developing countries are making concerted efforts to reduce their dependence on oil exporting countries, and pollution levels through policies to produce bio-ethanol and bio-diesel for blending with petrol and fossil diesel, respectively. China is now home to the world's largest ethanol plant, with a capacity of eight times that of the average US distillery. Two distilleries are coming up in the Philippines. The list of world's top bio-fuel producers and primary feedstocks in 2004 is provided in Table 1.

Table 1. World's top Bio-fuel Producers, 2004.

Country	Amount (million liters)	Share of the world production (%)	Primary feed stocks
Ethanol			
Brazil	15,110	37	Sugarcane
United States	13,390	33	Maize
China	3,650	9	Maize, cassava and cereal grains
India	1750	4	Sugarcane molasses, cassava
France	830	2	Sugar beets, wheat
Bio-diesel			
Germany	1,310	50	Rapeseed, sunflower seed
France	440	17	Rapeseed,
Italy	400	15	Sunflower seed, rapeseed
United States	95	4	Soybean
Denmark	88	3	Rapeseed

Source: State of the World, 2006.

Ethanol- the most promising biofuel

I. Sweet sorghum: Sweet sorghum is similar to grain sorghum but features more rapid growth, higher biomass production, wider adaptation, and has great potential for ethanol production. Sweet sorghum being a C_4 species is more water-use efficient and can be successfully grown in semi-arid tropics, where other crops such as maize fail to thrive (Table 2).

Table 2. Water use efficiency of sorghum in comparison to maize

Crop	Water use efficiency (Kg water/kg dry matter)
Sorghum (Lima, 1998)	310
Maize (Chapman and Carter 1976),	370

The dual-purpose nature of sweet sorghums—they produce both grain and sugar-rich stalks—offers new market opportunities for smallholder farmers and does not threaten food, feed and fodder value of sorghum. Sorghum is being cultivated since time immemorial in several countries of Asia and Africa. Incidentally, most of the landraces that are being grown in India in post-rainy season are sweet sorghums. In China, specific programs are underway to breed sweet sorghums for silage production. The emerging bio-fuel needs, therefore offer expanded markets for sweet sorghum in India, China and several African countries. Because sweet sorghum requires less water and has a higher fermentable sugar content than sugarcane, which contains more crystallizable sugars, it is better suited for ethanol production than sugarcane or other sources, and sweet sorghum ethanol is cleaner than sugarcane ethanol, when mixed with gasoline. Pilot studies in India indicated that ethanol production from sweet sorghum is cost-effective. Also, the net returns from sweet sorghum cultivation at the prevailing cost of cultivation and ethanol prices is about 10% higher than that from grain sorghum (Table 3) in India. The results may be similar with other bio-ethanol crop options.

Table 3. Potential ethanol yields by feedstock in Sub-Saharan Africa

Feedstock	Biomass yield (tons year^{-1})	Ethanol yield (liters ton^{-1})	Ethanol yield (liters/ha year^{-1})
Molasses	na	270	na
Sugarcane	50	70	3500
Sweet sorghum[1]	92	108	5000
Maize	6	370	2220
Cassava	12	180	2160
Wood	20	160	3200

Source: www.olade.org.ec/biocombustibles/documents/pdf-17.pdf; 1. For sweet sorghum at least two crops could be harvested per year in many parts of Africa, thus doubling the typical biomass yield per crop of 46 tons ha-^{1}

Comparative advantages of sweet sorghum*:* Sweet sorghum growing period (about 4.5 months) and water requirement (8000 m^3 over two crops) (Soltani and Almodares 1994) are 4 times lower than those of sugarcane (12−16 months duration and 36,000 m^3 of water crop^{-1}, respectively). Its cultivation cost is also four times lower than that of sugarcane. Sweet sorghum juice is better suited for ethanol production because of its higher reducing sugar content as compared to other sources such as sugarcane juice. These important traits, along with its suitability for seed propagation, mechanized crop production, and comparable ethanol production capacity *vis a vis* sugarcane molasses and sugarcane makes sweet sorghum a viable alternative raw material source for ethanol production Also, the cost of ethanol production from sweet sorghum is cheaper as compared to sugarcane molasses at prevailing prices (Table 4).

Table 4. Comparative advantages of sweet sorghum vs. sugarcane/sugarcane molasses for ethanol production

Crop	Cost of cultivation (Rs. ha^{-1})	Crop duration	Water requirement	Ethanol productivity (liters ha^{-1})	Cost of ethanol production (l^{-1})
Sweet sorghum	17820 over two crops	4.5 months	8000 m^3 over 2 crops	5600 year^{-1} over 2 crops (a)	13.11(d)
Sugarcane	44250 crop^{-1}	12-16 months	36,000m^3 crop^{-1}	6500 crop^{-1} (b)	
Sugarcane molasses	-	-	-	850 year^{-1} (c)	14.98(e)

(a) 70 t ha^{-1} millable stalk crop^{-1} @ 40 liters t^{-1}; (b) 85-90 t ha^{-1} millable cane crop-1@ 75 liters t^{-1}
(c) 3.4 t ha^{-1}@ 250 liters t^{-1}; (d) Sweet sorghum stalk @Rs.500 t ha^{-1}; (e) Sugarcane molasses @Rs.1600 t ha^{-1}
Source: Dayakar Rao et al. 2004

In addition to sweet stalks, grain yield of 2 to 2.5 t ha^{-1} can be obtained from sweet sorghum crop (this can be used as food or feed). The stillage from sweet sorghum after the extraction of juice has a higher biological value than the bagasse from sugarcane when used as forage for cattle, as it is rich in micronutrients and minerals. Additionally, the pollution level in sweet sorghum-based ethanol production has 1/4th of biological oxygen dissolved (BOD) i.e., 19,500 mg liter^{-1} and lower chemical oxygen dissolved (COD) i.e., 38,640 mg liter^{-1} compared to molasses-based ethanol production [as per pilot study conducted by Vasanthadada Sugar Institute (VSI) Pune, India]. Ethanol being a 'clean burning fuel' with high octane rating, the existing 4-wheeler automobile engines can be operated with petrol blended with ethanol without any need for engine modification (Table 5). Thus, sweet sorghum offers good prospects for ethanol production both from the point of economics of production as well as environmental protection (Table 6). Therefore the use of sweet sorghum for ethanol production is being given high priority by many developing countries including India. The demand for fuel ethanol in the countries targeted under this project can be met effectively if sweet sorghum is used along with current feedstock sources.

Table 5. Sweet sorghum score over sugarcane

As a crop	As ethanol source	As stillage
- Shorter gestation period - Dryland crop - Greater resilience - Farmer friendly - Meets fodder/ food needs	- Eco-friendly process - Superior quality - Less sulphur - High octane - Automobile friendly (up to 25%)	- Higher biological value - Rich in micronutrients - Use as feed/for power cogeneration

Table 6. Net earnings from sorghum.

	Sweet sorghum		**Grain sorghum**	
	Rainy	**Post-rainy**	**Rainy**	**Post-rainy**
Grain yield ($t\ ha^{-1}$)	1.0	2.0	3.0	2.0
Stalk yield ($t\ ha^{-1}$)	40	25	10	7
Grain value (US$ $annum^{-1}$)[3]	326		543	
Stalk value (US$ $annum^{-1}$)	707[1]		370[2]	
Total value (US$ $annum^{-1}$)	1033		913	
Leaf stripping (US$ $annum^{-1}$)	40		-	
Net value (US$ $annum^{-1}$)	993		913	

Data based on two crops per annum; on-station performance; [1]Sweet stalk @ US$ 10.87 t^{-1}; [2]Stover @ US$ 22 t^{-1}; [3]Grain @US$108.7 t^{-1}.

Progress in sweet sorghum research

Considerable progress has been made in breeding for improved sweet sorghum lines with higher millable cane and juice yields in India. A few of these cultivars have been released, e.g., SSV 84, SSV 74 and NSSH 104 (Reddy et al. 2005). The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) located at Patancheru in Andhra Pradesh, India, has developed several improved lines with high stalk sugar content and a few of these lines are being tested in pilot studies for sweet sorghum-based ethanol production in India, the Philippines and Uganda. Research experience at ICRISAT and elsewhere, shows that hybrids are known to produce relatively higher biomass, besides being early and photo-insensitive than other cultivar types under normal as well as abiotic stresses including water-limited environments. The requirement of photo- and thermo-insensitivity is essential to facilitate plantings at different dates for timely scheduling the supply of sweet sorghum stalks to distilleries for ethanol production (Reddy et al. 2005). The development of sweet sorghum hybrids should therefore receive high priority to produce more feedstock per drop of water and unit of energy invested. The ethanol, feed and grain productivity potential of some of the sweet sorghum hybrids developed at ICRISAT is provided in Table 7. It is possible to further improve the stalk total sugar yield to improve ethanol yield as there is significant variability for the stalk total sugar content and ICRISAT is poised to increase stalk sugar yield in hybrid parents (Table 8 and 9).

Table 7. Performance of selected sweet sorghum hybrids, 2006 rainy season, ICRISAT, Patancheru, India.

Hybrid	Days to 50% flowering	Brix	Juice Yield (kl ha^{-1})	Sugar yield (t ha^{-1})	Grain yield (t ha^{-1})	Per day ethanol productivity (l ha^{-1})$
ICSA 749 × SSV 74	85	18.00	27.15	9.15	3.28	18.48
ICSA 502 × SPV 422	88	20.32	19.88	8.12	6.15	14.11
ICSA 511 × SSV 74	88	17.97	22.70	7.84	5.79	15.39
ICSA 474 × SSV 74	82	16.33	25.42	7.57	7.19	17.13
SSV 84 (control)	94	15.65	16.84	4.98	2.67	10.50
NSSH 104 (control)	91	15.65	16.84	4.98	4.12	10.74

$ = Ethanol productivity estimated at 40 liters per ton of millable cane yield.

High-yielding designated hybrid parents with sweet stalk trait, and the varieties developed by crossing promising sweet sorghum lines were evaluated in replicated trials during the 2006 rainy season. Results of these trials are given below.

Sweet sorghum advanced B-line trial: Three B-lines, ICSB 729 (3.3 t ha^{-1}), ICSB 722 (3.1 t ha^{-1}), ICSB 321 (3.0 t ha^{-1}) were on par with the check SSV 84 (2.7 t ha^{-1}) for sugar yield. Among these, ICSB 722 (14 t ha^{-1}) was significantly better than the check 296 B (10.9 t ha^{-1}) for grain yield, while the rest of them were on par with 296 B, except ICSB 321. The performance of these lines for other traits is given in Table 8.

Table 8. Performance of advanced B-lines during the 2006 rainy season at ICRISAT, Patancheru.

B-line	Days to 50% flowering	Cane yield (t ha^{-1})	Juice yield (t ha^{-1})	Brix reading at maturity	Sugar yield based on Brix reading and juice yield (t ha^{-1})	Grain yield (t ha^{-1})	Per day ethanol productivity (l ha^{-1})*
ICSB 729	77	49.5	23.4	14.7	3.3	10.9	16.92
ICSB 722	75	41.5	20.5	15.2	3.1	14.0	14.43
ICSB 321	78	40.6	18.0	17.5	3.0	7.9	13.76
SSV 84 (Check)	82	45.7	18.6	18.2	3.3	3.0	14.98
296 B (Check)	69	12.1	2.7	8.3	0.5	10.9	4.44

Mean	67	21.5	9.2	12.9	1.2	11.4	8.04
CV (%)	1.69	12.5	21.11	9.33	30.3	11.84	-
CD (5%)	1.82	4.36	3.13	1.94	0.41	2.17	-

**Ethanol productivity estimated at 40 liters per ton of millable cane yield*

Sweet sorghum Varietal and Restorers trial: During the 2006 rainy season, 45 lines were selected and evaluated along with the checks SSV 74 and NSSH 104. A hybrid check (most promising) is also included in this trial to have a better comparison. Compared to the checks (SSV 74: 1.2 t ha^{-1} and NSSH 104: 1.1 t ha^{-1}), 14 varieties performed significantly superior for sugar yield (1.67 to 3.0 t ha^{-1}). Some of the lines had high brix reading but poor juice yield. They include IS 21991 (21.2), SP 4511-3 (21.0) and SP 4511-2 (20.0). These lines will be used in crossing program. The performance of top five high-yielding lines for sugar yield is given in Table 9.

Table 9. Performance of some promising varieties for per day ethanol productivity during the 2006 rainy season at ICRISAT, Patancheru.

Variety/restorer	Days to 50% flowering	Cane yield (t ha^{-1})	Juice yield (t ha^{-1})	Brix reading at maturity	Sugar yield based on Brix reading and juice yield (t ha^{-1})	Per day ethanol productivity (l ha^{-1})*
SP 4484-2	94	36.3	18.08	16.0	3.0	10.84
SP 4487-3	95	35.3	14.0	17.7	2.4	10.46
SP 4504-2	95	33.3	14.0	17.3	2.3	9.87
SP 4482-2	94	29.8	13.2	18.7	2.3	8.9
SP 4482-1	95	33.4	13.4	17.0	2.2	9.9
NSSH 104 (Check)	86	19.5	7.6	14.2	1.1	6.19
SSV 74 (Check)	88	18.9	6.5	18.7	1.2	5.91
Mean	94	20.6	7.6	16.2	1.2	6.15
CV (%)	1.9	27.8	23.5	12.0	28.9	-
CD (5%)	2.85	9.28	2.90	3.15	0.57	-

** Ethanol productivity estimated at 40 liters per ton of millable cane yield*

Research work at ICRISAT, Patancheru revealed that with delay in crushing of sweet sorghum stalks after harvest it reduces the sugar yields considerably (Table 10). Efforts are underway at ICRISAT, Patancheru for developing sweet sorghum male-sterile lines to delineate the method of producing sweet sorghum hybrids, and to study the effect of agronomic practices on sweet sorghum related traits.

Table 10.Reduction in ethanol-related traits in sweet sorghum with the delay in crushing after the harvest

Days after harvest	Cane yield (t ha^{-1})	Juice yield (t ha^{-1})	Juice extraction (kl ha^{-1})	Brix reading at maturity (t ha^{-1})	Sugar yield based on Brix reading and juice yield (t ha^{-1})	Reduction (%) in sugar yield under storage after harvesting
Same day	33.02	14.33	42.44	18.50	2.62	0.0
1	32.72	13.33	40.55	19.25	2.47	5.7
2	30.63	10.77	34.96	20.88	2.18	16.8
3	32.26	11.35	35.45	21.12	2.26	13.7
Mean	31.25	11.84	37.44	20.62	2.24	
SE±	4.40	2.14	2.60	0.83	0.44	
CV%	28.15	36.19	13.89	8.01	39.34	
CD (5%)	13.26	6.46	7.84	2.49	1.33	

Note: All the yield values are adjusted to overall mean of fresh stalk yield on harvested day.

Sweet sorghum hybrids vs. varieties: The selected sweet sorghum hybrids and varieties were compared at ICRISAT, Patancheru during the post rainy seasons in 2004 and 2005 for the changes in flowering time and Brix value with different dates of sowing in post rainy season. The results clearly indicated that hybrids were stable for flowering time irrespective of the sowing date compared to varieties (Fig 1). Large variation was observed in the varieties for days to 50% flowering with the change in date of sowing. For Brix value both hybrids and varieties behaved alike. Brix value was highest in November sown crop and decreased gradually up to February sown crop and then increased in March sown crop (Fig 2) indicating that early sowing helps in getting high brix value which important for ethanol production.

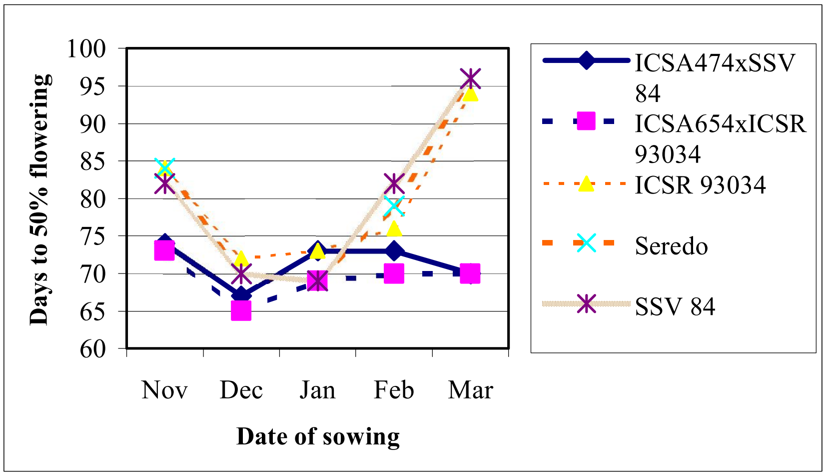

Fig 1. Variation in flowering time in selected sweet sorghum hybrids and varieties with different sowing dates at ICRISAT, Patancheru.

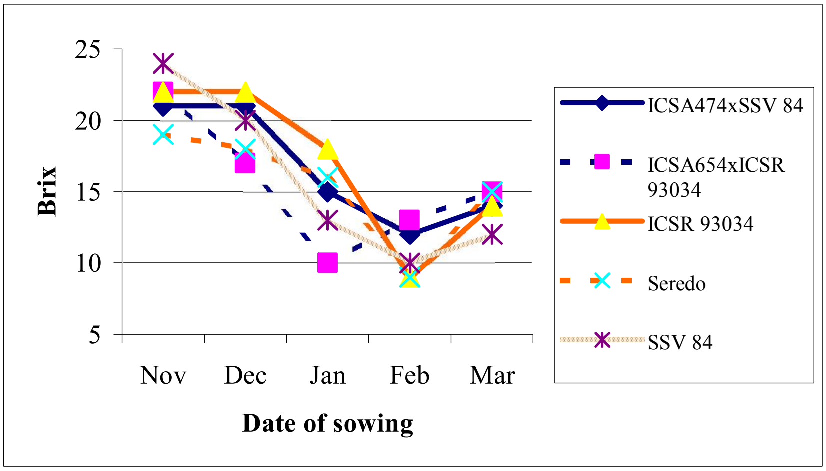

Fig 2. Changes in Brix value in selected sweet sorghum hybrids and varieties with different sowing dates at ICRISAT, Patancheru.

Sweet sorghum for ethanol production: public-private sector partnerships

ICRISATs mission is to reduce poverty, enhance food and nutritional security and protect the environment of the semi-arid tropics by helping empower the poor through science with a human face. It firmly believes in building public-private partnerships to help reach the goals by better harnessing of technology for commercialization. Towards making the sweet sorghum a viable supplement for ethanol production to meet the demand all over the world, ICRISAT is actively working with the National Agricultural Research Systems (NARS) partners in India, The Philippines, Uganda and Nigeria. Its tie up with Rusni Distilleries Ltd., through Agri-business Incubator (ABI) for the purpose of incubating the sweet sorghum based ethanol technology, which was commissioned by the Director General of ICRISAT in 2006 amply, demonstrated the commercial viability of this technology. It is the world’s first sweet sorghum based ethanol production distillery, and has become a model for the establishment of such industries world over.

II. Ligno-cellulose biomass. With the development of bio-catalysts-genetically engineered enzymes, yeasts, and bacteria, it is now possible to produce ethanol (what are called as second-generation bio-ethanol) from any plant or plant part known as ligno-cellulose biomass such as crop residues (stovers) of any cereal. Sorghum stover also serves as an excellent feedstock for ethanol production (Table 11).

Table 11. Potential of ligno-cellulosic biomass for ethanol production

Feedstock	Liters ethanol ton^{-1}
Sugarcane bagasse	500
Maize/sorghum/rice stover	500
Forest thinnings	370
Hardwood sawdust	450
Mixed paper	420

Source: Planning commission.nic.in/reports/genrep/cmtt_bio.pdf

Currently, a few countries with higher ethanol and fuel prices are producing ethanol from ligno-cellulose feedstocks (Badger 2002). The stovers contain lignin, hemi-cellulose, and cellulose. The hemi-cellulose, and cellulose are enclosed by lignin (which contains no sugars), making them difficult to reach and convert them into ethanol and hence energy requirement also escalates. Fortunately, available brown midrib maize mutants (originally described by Jorgenson 1931) and sorghum mutants (originally described by Porter et al. 1978) have significantly lower levels of lignin content (by 51% in stems and by 25% in leaves in sorghum and by 5 to 50% in maize stems). Brown midrib mutants are also available in sudan grass and pearl millet. Research at Purdue University, West Lafayette, Indiana, USA indicated 50% higher yield of fermentable sugars from certain maize and sorghum brown midrib mutants' stover after enzymatic hydrolysis (www.ct.ornl.gov/symposium/index_files/6Babstracts/6B_01.htm). The use of brown midrib crop cultivars as feedstocks would therefore reduce the costs of ethanol production, thereby making the price of ethanol competitive to that of fossil fuel. Also, considering that brown midrib types confer increased rumen digestibility, green fodder and stover from brown midrib crop cultivars would serve as excellent source of rumen dry matter requirement. Hence, it is worth making research investments on developing high biomass yielding brown midrib sorghum, sudan grass, maize and pearl millet hybrids which besides being cheaper source for bio-fuel production, meet fodder needs of subsistence farmer. ICRISAT research efforts in breeding sorghum brown midrib hybrid parents are yielding positive results (Table 12).

Table 12. Characteristics of selected sorghum brown midrib lines, 2002 rainy season, ICRISAT, Patancheru, India.

Line	Midrib color[1]	Brix reading at grain maturity (%)	Green fodder yield (t ha^{-1})	Grain yield (t ha^{-1})
White grain B-lines				
ICSB 293	1.5	13.8	20.8	4.0
ICSB 301	1.0	14.3	15.2	3.2
ICSB 418	1.5	17.3	19.0	2.5
ICSB 472	1.5	20.3	27.4	2.5
ICSB 474	1.0	17.5	15.3	1.6
ICSB 507	1.5	15.5	24.5	2.0
ICSB 664	1.5	22.9	26.9	1.7
ICSB 702	1.5	13.8	23.7	3.4
ICSB 731	1.5	18.0	34.6	3.3
ICSB 765	1.5	17.0	15.1	2.3
Red grain varieties				
ICSV 96114	1.5	17.3	17.6	3.1
GD 65025	1.5	22.0	34.4	0.6

1. Midrib color at harvest on a 1–5 scale; where, 1 = more brown and 5 = more white.

Crop improvement specialists should therefore aim for developing crop cultivars with high-density biomass production ability (for example, 10 tons stover per hectare in maize; 15 tons stover per hectare in sorghum) and enhanced water- and nutrient-use efficiency under resource-conserving systems that provide an overall energy savings and cut emissions of carbon dioxide and pollutants.

References

1. Badger PC.2002. Ethanol from Cellulose: A general Review. Pages 17–20 in Trends in new crops and new uses (Janick J. Ed.). ASHS Press, Alexandria, VA, USA.

2. Chapman, S.R., and Carter, L.P. 1976. Crop production, principle and practices. San Francisco: W.H. Freeman. 566 pp.

3. Dayakar Rao B, Ratnavathi CV, Karthikeyan K, Biswas PK, Rao SS, Vijay Kumar BS and Seetharama N. 2004. "Sweet Sorghum cane for bio-fuel production: A SWOT analysis in Indian context", National Research Center for Sorghum, Rajendranagar, Hyderabad, Andhra Pradesh 500 030, India. 20pp.

4. Lima, G.S. de. 1998. Estudo comparativo da resistencia a' seca no sorgo forrageiro (*Sorghum bicolor* (L.) Moench) em differentes estadios de desenvolvimento. Recife: UFRPE.128 p.

5. Ortiz R., Crouch JH, Iwanaga M, Sayre K, Warburton M, Araus J, Dixon J, Bohn M, Reddy BVS, Ramesh S and Wani S. 2006. Bio-energy and agricultural research-for-development. Vision 2020 for Food Agriculture and the Environment: Agriculture and Energy in Developing Countries 8. 2 pp.

6. Reddy BVS, Ramesh S, Sanjana Reddy P, Ramaih B, Salimath PM and Rajashekar Kachapur. 2005. Sweet sorghum–A potential alternative raw material for bio-ethanol and bio-energy. International Sorghum and Millets Newsletter 46:79–86.

7. Soltani A and Almodares A. 1994. Evaluation of the investments in sugar beet and sweet sorghum production. National Convention of Sugar Production from Agricultural Products, 13–16 March 1994, Shahid Chamran University, Alwaz, Iran.