Indian J.Dryland Agric. Res. & Dev. 2011 26(1) : 65-71

Sweet Sorghum *(Sorghum bicolor* (L.) Moench) - A New Generation Water Use Efficient Bioenergy Crop

P. Srinivasa Rao[1], J.V.N.S. Prasad[2], A.V. Umakanth[3] and Belum V.S. Reddy

[1] *International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India. Email: p.srinivasarao@cgiar.org*

[2] *Central Research Institute for Dryland Agriculture, Santoshnagar, Hyderabad-500 059*

[3] *Directorate of Sorghum Research, Rajendranagar, Hyderabad-500 030*

ABSTRACT: Biofuels have been widely recognized as a best alternative to insulate emerging economies against fastly depleting fossil fuels coupled with highly volatile prices. Sweet sorghum is a multipurpose bioethanol feedstock with greater adaptability with triple benefits (food, fodder and fuel) and cannot be part of much debated food vs. fuel issue. This article gives a brief overview of research results on water use and water use efficiency of sweet sorghum, a new generation bioenergy crop. This feedstock performs superior at many locations in terms of resource use efficiency vis a vis sugarcane, corn and tropical sugar beet and scores fairly well for adaptation to dry land conditions due to its inherent characteristics.

Key words: bioenergy, bioethanol, sweet sorghum, water use, water use efficiency, adaptability

Production of adequate and reliable quantum of food and energy is essential for socio-economic development and poverty alleviation of emerging economies, which can be made possible through provision of sufficient nutrition and income to satisfy health and other needs. It is estimated that by 2050, 9.3 billion people will share the Earth's surface (U.S. Census Bureau, 2010). Hence, the demand for food, feed and energy will increase worldwide resulting in huge pressure on the resources of both developing and developed nations. According to the Food and Agricultural Organization of the United Nations (FAO, 2005), fossil fuels are the most important energy source worldwide and their excessive use is the primary cause for global warming and climate change. Global crude oil price volatility is unprecedented and unpredictable than ever before as seen in 2008. In January 2008, the price of crude oil per barrel in the international market was $88.92. Crude oil price rise is now a crude reality. In June 2008, it touched a historic high of $147 per barrel mark, and it rock bottomed to $33 per barrel in December 2008 owing to global economic recession and again increased to $80 in June 2010. Therefore, economic, environmental and energy security concerns resulting from excessive reliance on fossil fuels like petroleum are forcing countries throughout the world to shift to eco-friendly alternatives like biofuels, and the mandated targets for some of the countries are given in Table 1. The driving forces behind bioenergy development are the need to insulate economies from volatile petroleum prices, but also its potential capacity to reduce global greenhouse gas emissions and to enhance farmers' income. Biofuels may have potential benefits such as diversification of agriculture output and domestic energy supply, development of infrastructure and job creation in rural communities and enhancing income opportunities from the use of agriculture produce and by products besides from carbon credits. Since biofuels can be produced from a diverse set of crops, each country is adopting a strategy that utilizes the comparative advantages it holds with respect to such crops. For example, sugarcane and maize are the main feedstocks for ethanol in Brazil and US respectively, Cassava in Colombia, sugarcane molasses and sweet sorghum (limited scale) in India, while rapeseed in Europe, and palm oil in Malaysia are the main feedstock's for biodiesel. The bioethanol productivity of popular feedstocks is given in Table-2. Sugarcane and corn are the major bioethanol feedstocks both in terms of production and area globally. The recent shifts in biofuel policies of many developing nations aims to generate several other benefits like employment for the rural poor, regeneration of wastelands, reduction of carbon emissions resulting from energy use that will have socio-economic and environmental ramifications (Rao and Bantilan, 2007).

Table 1 : Voluntary and mandatory bioenergy targets for transport fuels in G 8+5 countries

Brazil	:	Mandatory blend of 20–25 percent anhydrous ethanol with petrol; minimum blending of 3 percent biodiesel to diesel by July 2008 and 5 percent (B5) by end of 2010
Canada	:	5 percent renewable content in petrol by 2010 and 2 percent renewable content in diesel fuel by 2012
China	:	15 percent of transport energy needs through use of biofuels by 2020
France	:	5.75 percent by 2008, 7 percent by 2010, 10 percent by 2015 (V), 10 percent by 2020 (M = EU target)
Germany	:	6.75 percent by 2010, set to rise to 8 percent by 2015, 10 percent by 2020 (M = EU target)
India	:	10% by 2012 and 20% by 2017
Italy	:	5.75 percent by 2010 (M), 10 percent by 2020 (M = EU target)
Japan	:	500 000 kilolitres, as converted to crude oil, by 2010 (V)
South Africa	:	Up to 8 percent by 2006 (V) (10 percent target under consideration)
United Kingdom	:	5 percent biofuels by 2010 (M), 10 percent by 2020 (M = EU target)
United States of America*	:	9 billion gallons by 2008, rising to 36 billion by 2022 (M). Of the 36 billion gallons, 21 billion to be from advanced biofuels (of which 16 billion from cellulosic biofuels)
European Union	:	10 percent by 2020 (M proposed by EU Commission in January 2008)

M = mandatory; V = voluntary. * The United States carries no mandatory renewable energy targets.
(**Source**: The state of food and Agriculture. Biofuels: Prospects, Risks and Opportunities, FAO 2008)

Table 2 : Global bioethanol yields of popular feed stocks

Feedstock	Productivity (t ha^{-1})	Conversion efficiency (Lt^{-1})	Bioethanol yield (L)
Sugarcane	65	70	4550
Sugar beet	46	110	5060
Corn	4.9	400	1960
Cassava	12	180	2070
Grain sorghum	1.3	380	494
Rice	4.2	430	1806
Wheat	2.8	340	952
Sweet sorghum*	30-45	50	1500-2250

(**Source**: The state of food and agriculture. Biofuels: prospects, risks and opportunities, FAO 2008) * data from large scale experiments of ICRISAT (2007-2009) and small scale cultivation in Andhra Pradesh and Maharastra, India.

Sweet sorghum, *Sorghum bicolor* (L.) Moench, is considered a new generation bioenergy crop owing to its multiple uses and wider adaptability to varied agro-climatic conditions. This crop is similar to grain sorghum except for juice rich sugary stalks that grows rapidly, yielding higher biomass but sensitive to photoperiod and temperature similar to other sorghums. Sweet sorghum being a C_4 species is more water-use efficient and can be cultivated in areas lying between 40^0 South and North latitudes of equator (Rao *et al*., 2009). Among different biofuel feedstocks, sweet sorghum is of particular interest because its biomass is variously used for the production of energy, fiber or paper, as well as for syrup and animal feed, while grain is either used for human consumption or for ethanol production or as feed. This is the only feedstock where ethanol can be produced through either grain or sweet juice or syrup or biomass, in other words having relevance to first, second and third generation biofuels. Sweet sorghum has many useful traits such as a drought resistance (Tesso *et al*., 2005), water logging tolerance, salinity resistance (Almodares *et al*., 2009) and with a high biomass yield. The growth and production of sweet sorghum under semi-arid conditions in the South Asian and Sub-Saharan Africa environments are constrained by both mid season and terminal moisture stresses. Mid season stress is common in rainy season crop while terminal stress is frequent in post rainy season crop. However, inherent traits such as extensive root system (roots are normally concentrated in the top 90 cm of soil but may extend to twice that depth and to 1.5 m in lateral spread) and waxy bloom on the leaves that reduces water loss contributes to its adaptation to dry conditions. The objective of this article is to shed light on the limited current research reports on water use and water use efficiency of sweet sorghum in semi-arid and Mediterranean environments.

Water use and irrigation

Grain sorghum is grown under rainfed conditions with little or no irrigation in the sub continent. Sorghum is widely reported to tolerate drought conditions and prolonged periods of moisture stress during the crop growth period. It can survive with a supply of less than 300 mm rainfall over a season of 100 days, can become relatively dormant during periods of water stress and responds favorably with additional rain fall or irrigation water. The water use of sorghum ranges from 537- 580 mm and lower in comparison to corn which is about 760 mm (Mastrorilli *et al* 2002). Cultivation of sweet sorghum is advisable in areas that receive more or less uniform distribution of 700 mm annual rainfall and one or two irrigations improve the yields substantially. The critical growth stages of sweet sorghum in relation to water requirement are: the grand growth stage, 20-25 days after sowing (DAS), flag-leaf stage or boot stage, 50-55 DAS and flowering stage, 70-75 DAS. The experience at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and Directorate of Sorghum Research (DSR) revealed that sweet sorghum requires 2-3 irrigations based on rainfall pattern during the rainy season and 5-6 irrigations during the postrainy season while tropical sugar beet needs as many as 15 in vertisols and 17 irrigations in alfisols. Therefore, sweet sorghum is uniquely adapted to limited irrigation conditions unlike maize, sugarcane, sugar beet etc. (Reddy *et al*., 2005).

Irrigation water had direct effect on the growth and yield of sweet sorghum. Application of irrigation at IW:CPE of 0.6 results in higher yields (Sudarshan *et al* 2009). Irrigating sweet sorghum more frequently than at 50% depletion of plant available soil moisture does not found to increase ethanol yield and reduced biomass produced per unit of water (Miller and Ottman (2010). Mastrorilli *et al* (1999) suggested phonological basis for irrigating sweet sorghum for optimizing irrigation under limited water situations and suggested that sweet sorghum should be irrigated when the pre- dawn leaf water potential falls to values -0.4 Pa. which is attained when the soil reaches the wilting point. Sweet sorghum grown under more frequent irrigations (every 3 days) and the greatest water amount (30 mm) gave the highest plant height, stem dry weight and stem fresh weight yield whereas those grown under the least irrigation frequency (every 15 days) and fewest water amount (10 mm) gave the lowest. The lowest irrigation frequency and water amount reduced transpiration rate, relative water content and total conductance but increased leaf temperature. However, there were no interaction among sweet sorghum cultivars, irrigation frequencies and water amounts (Vannavong and Detpiratmongkol, 2007). It was found that above-ground dry biomass production from non-water-stressed sweet sorghum plants suggests a high productivity potential among C4 crops. Crop growth can be improved by rain water conservation techniques such as surface mulching, ridge and furrow rainfall harvesting system, gravel sand mulching, plastic mulching and straw mulching (YaJun *et al* 2009). Crop yield and WUE were higher with plastic-covered ridges and with gravel-sand-mulched furrows than bare ridges and furrows in semi arid regions of china. These findings suggested, the integrated use of rain water harvesting systems in combination with mulching and supplementary irrigation improves crop yield substantially (YaJun *et al* 2009).

The effect of temporary water stress on yield was dependent on the phenological stage during which it was applied. Water stress applied during the early vegetative growth period can potentially diminish the crop yield by 20%, biomass production was reduced by 36% when stress occurred during the stem elongation stage, but a stress period later in the vegetative cycle only slightly decreased stalk production which is less sensitive to soil water stress. (Mastrorilli *et al*, 2002). Occurrence of water stress during the later phenological stages slightly decreased stalk production (Mastrorilli *et al*., 1995 and Mastrorilli *et al*., 1999). Yield reduction resulting from post-anthesis irrigation stopage is very little. Geng *et al*. (1989) found that terminating irrigation 12 week before harvest had little effect on biomass yield. Under water shortage, radiation use efficiency may be significantly lower. Radiation use efficiency seems to be linearly related to water consumption. Stressed plants (probably except severely stressed) seem to use available water more efficiently than unstressed plants (Dercas and Liakatas 2007). Therefore, rainfed sweet sorghum in South Asia and Sub-Saharan Africa can be grown with less water.

Water use efficiency

Sweet sorghum has the unique property of becoming relatively dormant during periods of water stress (Smith and Buxton, 1993) and initiate rapid growth after the release of stress either by rainfall or irrigation, unlike maize. Sweet sorghum transforms the intercepted radiation (PAR) into dry matter at a higher efficiency i.e. 3.7 g of dry matter MJ m^{-2} (Radiation use efficiency, RUE) *vis a vis* sugarcane (2.7), maize (2.1-3.2), pearl millet (3) and has the highest water use efficiency (WUE) 193 mm kg^{-1} where as soybean requires 357 mm, sunflower 278 mm and grain sorghum 270 mm. Lima (1998) reported that sorghum requires 310 Kg of water to produce one Kg of biomass while maize consumes 23% more water i.e.370 kg to produce same quantity of biomass (Chapman and Carter, 1976). In an another study from Iran, Almodares *et al* (2009) showed that sweet sorghum consumes 12000 m^3 water during four months crop cycle while sugarcane requires 36000 m^3 in 9 months and sugar beet 18000 m^3 in 6 months. In Mediterranean conditions, sweet sorghum produced the highest biomass per unit area (up to 32 t ha^{-1} of dry matter), and has highest water consumption (550 mm) in comparison with soybean (344 mm) or sunflower (400 mm), and similar to that of grain sorghum (545 mm). Higher water use efficiency of sweet sorghum variety Keller was also reported in Europe. The water use efficiency varied from 3.74 to 5.43 g aerial bio mass dm^{-3} in experiments in Spain (Curt *et al* 1995) and high rates of water use efficiency was noticed by Dercas *et al*, (1995) in central Greece which ranged from 62-80 kg ha^{-1} mm^{-1}. Under non limiting conditions of water supply and mineral nutrition, the superior performance of sweet sorghum among various crops in terms of the water use efficiency (WUE) and radiation use efficiency (RUE) was reported by Mastrorilli *et al*., (1995). The 4-year average RUE is 1.78 g of biomass per MJ of solar radiation intercepted, and the WUE is 5.2 g of biomass per kg of water used and observed to be higher than those of maize and grain sorghum in independent experiments carried out in Spain, Greece, and three locations in Southern Italy (Goose, 1996). In tropical Brazil, where sugarcane is grown for biofuel, under rainfed conditions with limited irrigation, it takes only 90 liters of irrigation water to produce a liter of ethanol. But, in India, where sugarcane depends heavily on irrigation, 3,500 liters of irrigation water is required. Similarly rainfed maize in USA requires 400 litres of water while irrigated maize in North china consumes 2400 litres (de Fraiture *et al* 2008).

Under water shortage, RUE may be significantly lower affecting sweet sorghum productivity. RUE seems to be linearly related to water consumption. Stressed plants (probably except severely stressed) seem to use available water more efficiently than unstressed plants. Yield reduction resulting from post-anthesis irrigation stopage is very little. High water use efficiency values tend to be related with low radiation use efficiency values (Dercas and Liakatas 2007). Sweet sorghum photosynthetic water use efficiency appear to vary with pre-dawn water potential and vapour pressure deficit at both leaf and canopy scales, parallel behaviour occurred between leaf and canopy scales in terms of gas exchange variables (Mustafa and Pasquale 2000).

In a study on photosynthetic water-use efficiency of leaves (WUE_1) and canopy (WUE_2) of sweet sorghum, in terms of gas-exchange responses, a parallel behavior was observed at both the leaf and canopy scale. This was particularly evident when comparing diurnal trends of WUE_1 and WUE_c. The resulting value of WUE_c, normalized for the evaporative demand of the atmosphere (E_o), was 1.56 mol CO_2 m^{-2}. While WUE_1 of sweet sorghum compared well with that of other C_4 crops, values at the canopy scale were higher than other C_4 crops, especially maize and grain sorghum. A possible explanation for a high WUE may be found in the differences in dark respiration of the whole canopy between sweet sorghum and other C_4 crops (Steduto *et al* 1997).

Water application, ethanol yield and quality

Water stress induced at the end of the season may be a method of increasing sugar yields of sweet sorghum similar to sugarcane production practices (Inman-Bamber, 2004). Previous studies reported mixed results on using water stress to increase sugar content of sweet sorghum. In an experiment, the irrigated crop produced more biomass (89.9 t ha^{-1}) compared with the rainfed crop (65.0 t ha^{-1}), but total sugar yield and theoretical ethanol were not significantly different (Smith and Buxton, 1993).

A study conducted in California, USA by Geng *et al.* (1989) reported a higher hexose yield in water-stressed production compared with an adequately watered crop. Results from Massacci *et al*. (1996) indicated that sugar accumulation (fresh weight basis) from drought-stressed plants was greater than from well irrigated plants at physiological maturity. In contrast to the work cited above, a study by Curt *et al*. (1995) conducted in Spain, showed that sweet sorghum grown in lysimeters with 5.7, 11.4, and 17.1 mm ha^{-1} d^{-1} during the grand growth stage didn't significantly affect sugar content of the stalks, but showed that the most stressed plants had a higher ratio of ethanol production. Limited experiments at ICRISAT, during the postrainy season also points to increased sugar yield at 15 days post-physiological maturity by 15-30% but varying with genotype.

Conclusions:

The importance of alternative sources energy that has relevance to socio-economic development and environmental security is bound to increase to overcome negative consequences of fossil fuel usage. Sweet sorghum produces more biomass per unit area and per unit time and per unit water due to its inherent characteristics- short duration, plasticity to environmental conditions, multipurpose nature meeting the demands of humans and livestock and high WUE and RUE etc. WUE primarily varies widely with respect to locations, time, management practices, and phenological stage, genotype and soil properties.

References

Almodares, A., Hadi, M.R. and Ahmadpour H. 2009. Production of bioethanol from sweet sorghum : A review. African Journal of Agriculture Research 4 (9) : 772-780.

Chapman, S.R. and Carter, L.P. 1976. Crop production, principle and practices. San Francisco: Freeman WH. 566 Pp.

Curt, M.D., Fernandez, J and Martinez, M. 1995. Productivity and water use efficiency of sweet sorghum (*sorghum bicolor* (L.) Moench) CV. "Keller" in relation to water regime. Biomass Bioenergy, 8(6) : 401-409.

de Fraiture, C., Giordano, M. and Liao, Y. 2008. Biofuels and implications for agricultural water use: Blue impacts of green energy. Water Policy Volume 10 Supplement I, pp. 67-81. (http://www.iwmi.cgiar.org/ EWMA / files/ papers/ Biofuels-Charlotte.pdf).

Dercas, N., and Liakatas, A. 2007. Water and radiation effect on sweet sorghum productivity. Water Resources Management, 21 : 1585–1600.

Dercas, N., Panovtsov, C., Dalians, C., Souter, C. 1995. Sweet sorghum (sorghum bicolor (L.) Moench) in: chartier, *et al* (Eds) Proceedings of English E.C Conference on response to four irrigation and two nitrogen fertilization rates. Biomass for energy, Environment, Agriculture, vol 1Pergamon press UK, Pp 629-639.

FAO 2008. The state of food and agriculture. Biofuels: Prospects, Risks and Opportunities. FAO, Rome, Italy.

FAO 2005. Bioenergy. Available at http://www.fao.org/docrep/meeting/009/j4313e. html. FAO, Rome, Italy.

Geng, S, Hills, F.J., Johnson, S.S. and Sah, R.N. 1989. Potential yields and on farm ethanol production cost of corn, sweet sorghum, fodderbeet, and sugarbeet. Journal of Agronomy and Crop Science, 162 : 21–29.

Inman-Bamber, N.G. 2004. Sugarcane water stress criteria for irrigation and drying off. Field Crops Research, 89 (1) : 107–122.

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.

Massacci, A., Battistelli, A., and Loreto, F. 1996. Effect of drought stress on photosynthetic characteristics, growth and sugar accumulation of field grown sweet sorghum. Australian Journal of Plant Physiology, 23:331–340.

Mastrorilli, M., Colucci, R., Bari, V. di., Montemurro, F. 2002. Sweet sorghum and irrigation. Rivista di Agronomia, 36 (4) : 319-325.

Mastrorilli, M., Katerji, N., and Rana, G. 1999. Productivity and water use efficiency of sweet sorghum as affected by soil water deficit occurring at different vegetative growth stages. Europian Journal of Agronomy, 11 : 207–215.

Mastrorilli, M., Katerji, N., Rana, G., and Stedunto, P. 1995. Sweet sorghum in Mediterranean climate: radiation use and biomass water use efficiencies. Industrial Crops and Products, 3 : 253-260

Miller, N.A., and Ottman, J.M. 2010. Irrigation frequency effects on growth and ethanol yield in sweet sorghum. Agronomy Journal, 102 : 60–70.

Mustafa, U., and Pasquale, S. 2000. Comparision of photosynthetic water use efficiency of sweet sorghum at canopy and leaf scales. Turkish Journal of Agricultural Forestry, 24 : 519-525

Rao, P.P., and Bantilan, M.C.S. 2007. Emerging biofuel industry: A case study for pro-poor agenda with special reference to India. GT IMPI Policy Brief No. 12., Patancheru, International Crops Research Institute for Semi-Arid Tropics.

Rao, P.S., Rao, S.S., Seetharama, N., Umakanth, A.V., Sanjana Reddy, P., Reddy, B.V.S. and Gowda, C.L.L. 2009. Sweet sorghum for biofuel and strategies for its improvement. Information Bulletin No. 77. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics. 80 Pp. ISBN:978-92-9066-518-2.

Reddy, B.V.S., Ramesh, S., Sanjana Reddy, P., Ramaiah, B., Salimath, P.M. 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.

Smith, G.A. and Buxton, D.R. 1993. Temperate zone sweet sorghum ethanol production potential. Bio Resource Technology, 43 : 71–75.

Steduto, P., Katerjib, N., Puertos-Molinaa, H., Unlua, M., Mastrorillic, M. and Ranac, G. 1997. Water-use efficiency of sweet sorghum under water stress conditions gas-exchange investigations at leaf and canopy scales. Field Crops Research, 54:221-23.

Sudharsan, P., Kalyanasundaram, D., Kavitha, S. 2008 Water use efficiency and economics of irrigation and nutrient management in sweet sorghum. Research on Crops, 9 (1) : 24-26.

Tesso, T.T., Claflin, L.E. and Tuinstra, M.R. 2005. Analysis of stalk rot resistance and genetic diversity among drought tolerant sorghum genotypes. Crop Science, 45 : 645-652

U.S., Census Bureau, Population Division. 2010. http://www.census.gov/ipc/www/idb/worldpop.php.

Vannavong, W., Detpiratmongkol, S. 2008. Effect of irrigation frequencies and water amounts on growth and yield of sweet sorghum. Proceedings of the 46th Kasetsart University Annual Conference, Kasetsart, 29 January - 1 February, 2008.

Wang YaJun, Xie ZhongKui, Malhi, S.S., Vera, C.L., Zhang YuBao, Wang JinNiu. 2009. Effects of rainfall harvesting and mulching technologies on water use efficiency and crop yield in the semi-arid Loess Plateau, China. Agricultural Water Management, 96 (3) : 374-382.