Sweet sorghum for biofuel and strategies for its improvement

Information Bulletin No. 77

ICRISAT
Science with a human face

भाकृ अनुप
ICAR

ज्वा अनु नि
DSR

Citation: Srinivasa Rao P, Rao SS, Seetharama N, Umakath AV, Sanjana Reddy P, Reddy BVS and Gowda CLL. 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 Order code: IBE 077.

Abstract: Self-sufficiency in energy requirements is critical to the success of any emerging economy. Renewable sources of energy are considered to be one of the major pillars of energy security that reduces dependence on fossil fuels besides negating the negative effects on the environment. Sweet stalked sorghums, popularly referred to as sweet sorghums, are multipurpose crop plants that provide food, fodder, feed, fiber and fuel at affordable prices to the rural poor, grows well in areas receiving more than 700 mm annual rainfall and located between 40° south and north of the equator. Popularization of this crop in semi-arid tropic (SAT) areas will bring smallholder and marginal farmers, besides rural poor, into the biofuel revolution as it enhances socio-economic returns on their holdings. In addition to providing a comprehensive latest global bioethanol scenario, Clean Development Mechanism (CDM) and Life Cycle Assessment (LCA) of biofuels, this information bulletin makes an attempt to describe and discuss the different issues impeding the productivity of sweet sorghum, conventional and molecular methodologies/tools to enhance sugar yield without hampering grain yield. This bulletin also gives a bird's eye view of the development of high biomass low lignin sorghums amenable for second generation ethanol production and different value chain linkage models with an emphasis on sweet sorghum improvement programs at ICRISAT and elsewhere.

About DSR: Directorate of Sorghum Research (DSR) (Formerly National Research Centre for Sorghum) was established on 16 November, 1987 by the Indian Council of Agricultural Research (ICAR). DSR is the nodal agency in the country dealing with all aspects of sorghum research, and development including coordination and consultancy. DSR works closely with many other sister institutions of ICAR, State Agricultural Universities and national and international agencies such as ICRISAT and other institutions both in the public and private sector. DSR is also mandated with organizing and coordinating sorghum research at all India level through All India Coordinated Sorghum Improvement Project (AICSIP), a network of 16 centers located in states having major sorghum growing area.

Acknowledgments: The authors highly appreciate the financial support by International Fund for Agriculture Development (IFAD) through the project entitled “Linking the poor to global markets: Pro-poor development of biofuel supply chains” (Grant no. 974). We also thank Dr Robert Schaffert for sharing the information on sweet sorghum varieties developed at Embrapa, Brazil.

Sweet Sorghum for Biofuel and Strategies for its Improvement

P Srinivasa Rao, SS Rao, N Seetharama, AV Umakanth, P Sanjana Reddy,
BVS Reddy and CLL Gowda

Information Bulletin No. 77

Indian Council of Agricultural Research
Krishi Bhavan, New Delhi - 110 114, India

Directorate of Sorghum Research
Rajendranagar, Hyderabad 500 030, Andhra Pradesh, India

International Crops Research Institute
for the Semi-Arid Tropics

Patancheru 502 324, Andhra Pradesh, India

About the authors

P Srinivasa Rao
Scientist (Sorghum Breeding)
p.srinivasarao@cgiar.org

SS Rao
Principal Scientist
ssrao@nrcsorghum.res.in

N Seetharama
Director, DSR
Seetharama@nrcsorghum.res.in

AV Umakanth
Senior Scientist
umakanth@nrcsorghum.res.in

Belum VS Reddy
Principal Scientist (Sorghum Breeding)
b.reddy@cgiar.org

P Sanjana Reddy
Scientific Officer (Sorghum Breeding)
sanjanareddy@cgiar.org

CLL Gowda
Global Theme Leader - Crop Improvement
c.gowda@cgiar.org

Contents

Page No.

Foreword

Renewable energy as a means of reducing dependency on fast depleting fossil fuels and also as an appropriate mechanism to reduce greenhouse gas (GHG) emissions is attracting the attention of many nations the world over. The urgent need to mitigate the adverse effects of climate change being experienced today is sinking in.

Keeping this in mind, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) launched a **BioPower** initiative to empower the dryland poor to benefit from, rather than be marginalized by, the biofuels revolution. The institute's research strategy focuses on feedstock sources and approaches with multiple advantages in partnership with national agricultural research systems (NARS).

Sorghum [*Sorghum bicolor* (L.) Moench] as a feedstock for biofuels has rapidly caught the attention of researchers, farmers and entrepreneurs worldwide. The hardy and multipurpose sweet sorghum plant provides grain for human consumption, stalks/leaves for animal fodder and the juice of the stalks for fuel. This it does without competing with the world's food basket or causing harm to the environment.

Sweet sorghum can be grown in the dry or semi-arid tropics across the globe as a rainfed crop in areas with annual rainfall of about 700 mm. The crop requires comparatively less fertilizer, water, labor and other inputs than sugarcane and maize. Being a C_4 plant, it has high photosynthetic efficiency (efficient in converting water and carbon-dioxide into carbohydrates). Since the crop takes about four months to raise, and can be followed by a ratoon crop, it is possible to harvest two crops per annum, thus maximizing crop productivity in areas with limited water availability. Though sweet sorghum has for the past several years been grown in certain pockets of Africa and northern America to make syrup and molasses, research on crop genetic improvement is of recent origin. Published scientific information on this "smart" crop is scanty.

Attempts have been made in India and around the world in the past to convert sweet sorghum juice to ethanol. Studies were initiated on genetic enhancement of "high energy" sorghums. The world requires energy to reduce the widening gap between demand and supply; therefore the heavy investment in sweet sorghum research.

This information bulletin provides exhaustive information on the global energy scenario, the present status of sweet sorghum in five continents, cultivars developed so far, constraints to commercialization, breeding methodologies including molecular tools to realize maximum selection efficiency and ways to overcome constraints, public-private sector partnerships, and a brief update on lignocellulosic ethanol production. Compiled by highly experienced scientists of ICRISAT and the Directorate of Sorghum Research (DSR, ICAR India), this lucid yet comprehensive publication is a valuable addition to the information bank on sweet sorghum. I am sure the bulletin will serve as an important source of reference to researchers, students, entrepreneurs, policy makers and other stakeholders.

William D Dar
Director General, ICRISAT

Acronyms

ACEEE	American Council for an Energy-efficient Economy
ADP	Adenosine di-phosphate
ADF	Acid detergent fiber
AFLP	Amplified fragment length polymorphism
ANOVA	Analysis of variance
ARS	Agricultural research service
ATP	Adenosine tri-phosphate
BAC	Bacterial artificial chromosome
BMP	Best management practices
bmr	Brown mid-rib
BOD	Biological oxygen dissolved
BRSLB	Experimental sweet sorghum bagasse/stripped leaves-based feed block
CAD	Cinnamyl aldehyde dehydrogenase
CDM	Clean development mechanism
CE	Cassava-based ethanol
CER	Certified emission reduction
CEY	Calculated ethanol yield
CFB	Commercial sorghum stover-based feed block
CFDT	Company for the development of the textiles
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COD	Chemical oxygen dissolved
COMT	Caffeic acid O-methyltransferase
DDGS	Distiller’s dried grains with solubles OR Dried distillers grains with solubles
DOE	Department of Energy (USA)
DSR	Directorate of Sorghum Research (formerly National Research Centre for Sorghum, NRCS)
EB	Executive board
ETS	Emission trading system
EU	European Union
EUBIA	European Biomass Industry Association
FAO	Food and Agriculture Organization
G×E	Genotype × environment
GCA	General combining ability
GHG	Greenhouse gases
GTL	Genome to life
IARC	International Agricultural Research Centers
ICAR	Indian Council of Agricultural Research

ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPEEC	Partnership for energy efficiency cooperation
KLPD	Kilo liters per day
LAMNET	Latin American Thematic Network on Bioenergy
LCA	Life cycle analysis
MAS	Marker-assisted selection
MABC	Marker assisted backcrossing
ME	Metabolizable energy
MIAME	Minimum information about a microarray experiment
MYMLT	Multi-year multi-location trial
N_2O	Nitrous oxide
NASS	National Agricultural Statistics Services
NARI	Nimbkar Agricultural Research Institute
NARS	National agricultural research systems
NDF	Neutral detergent fiber
NRCS	National Research Centre for Sorghum
NUE	Nutrient use efficiency
OECD	Organization for Economic Cooperation and Development
QTL	Quantitative trait loci
PDD	Project design document
PIC	Polymorphism information content
PIU	Period of industrial utilization
RFA	Renewable fuel association
RFLP	Restriction fragment length polymorphism
R&D	Research and development
RFG	Reformulated gasoline
RUE	Radiation use efficiency
SAT	Semi-arid tropics
SCA	Specific combining ability
SNP	Single-nucleotide polymorphism
SSR	Simple sequence repeats
TCL	Tata Chemicals Limited
TILLING	Targeting induced local lesions in genomes
UNEP	United Nations Environment Programme
UNICA	Brazilian sugarcane industry association
USA	United States of America
USDA	United States Department of Agriculture
USDOE	United States Department of Energy
VSI	Vasantdada Sugarcane Institute
WRI	World Resources Institute
WTO	World Trade Organization
WUE	Water-use efficiency

Introduction

Global population growth continues to rise at an alarming rate in spite of control measures taken by many countries. Predictions are that the population of the world will reach 9.4 billion by 2050 (US Census Bureau, 2006). The demand for food, fuel and energy resources of both developing and developed nations would increase substantially. According to the Food and Agricultural Organization of the United Nations (FAO 2005), fossil fuels are the most important energy source worldwide and also the primary cause for global warming and climate change.

In 2008, the volatility of global crude oil prices was unprecedented. On 21 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, and hit rock bottom at $33 per barrel in December 2008, owing to global economic recession; subsequently, it increased to $80 in November 2009.

The climate is changing and there is now scientific, social and political recognition that this is very likely a consequence of increasing anthropogenic greenhouse gas (GHG) emissions. Transport now accounts for about 20% of global anthropogenic carbon dioxide emissions and these figures are growing faster than for any other sector. However, access to energy underpins our current way of life and the hopes of people around the world for improved livelihoods. Mobility is a core component of these aspirations. Transport has become the main driver for increasing global primary oil demand, which is predicted to grow by 1.3% per year up to 2030, reaching 116 million barrels per day (up from 84 million barrels per day in 2005).

The continued escalation in crude oil prices will have serious repercussions at the global level, crippling the economies of developing and under developed countries, thus necessitating the monitoring of oil prices on a continuous basis by UN agencies and other world bodies. Many countries, including large economies like USA, China and India are importing huge amounts of petroleum products. Research on renewable sources of energy was initiated in many countries a few decades back especially after the oil shock in 1973. However, success was limited to Brazil, where ethanol distillation from sugarcane has been economically sustainable. Ethanol is blended with petrol for use in flexi-fuel vehicles in Brazil, reducing the dependence on 100% petrol.

The vast majority of today's ethanol is derived from starch- and sugar-based feedstocks. The sugars in these feedstocks are relatively easy to extract and ferment using widely available biochemical conversion technologies, making large-scale ethanol production affordable. Starch-based feedstocks include cereals such as corn, wheat and milo. Sugar-based feedstocks, such as sugarcane, sweet sorghum and sugar beets, contain simple sugars that can be extracted and fermented readily. Corn grain is the feedstock for more than 90% of current US ethanol production. High sugar yielding sweet sorghum is being utilized in India, the USA, the Philippines and other countries owing to the pioneering work at ICRISAT-Patancheru, Directorate of Sorghum Research (DSR), and All India Coordinated Sorghum Improvement Project (AICSIP) under the Indian Council of Agricultural Research (ICAR), India; Texas A&M University, Rutgers University and University of California (all in the USA); Mariano Marcos State University, the Philippines; CSIRO Plant Industry, University of Queensland and University of Melbourne (all in Australia).

This review covers the significance, research status in several areas, potential, food-fuel tradeoff and environmental implications of using sweet sorghum as feedstock for production of ethanol in the context of present food crisis and also global food vs fuel debate. It also briefly addresses the prospects of using sorghum stover/biomass/bagasse for ethanol production through second-generation lignocellulosic technology.

2. Renewable Sources of Energy

The present global energy requirements are met primarily from coal, oil, firewood and natural gas as shown in Figure 1. Renewable energy refers to sources of energy that do not irreversibly exhaust and deplete the sources overtime. It includes wind and solar energy and bio-based fuels such as ethanol, biodiesel and hydrogen. Wind and solar energy will be primarily of use in generating electricity for households and industry, whereas ethanol, biodiesel and hydrogen can be used as transportation fuel. While hydrogen is considered the ultimate green fuel, the technology and infrastructure to power cars with hydrogen are still in their infancy. In the short term, ethanol and biodiesel are considered the most promising alternative sources of fuel.

Biodiesel is produced from plant based oils and fat, either directly from edible oil-seeds {eg, soybean [*Glycine max* (L.) Merr.], oil palm [*Elaesis guineensis*. Jacq.], sunflower [*Helianthus annuus* L.], canola [*Brassica napus* L.]} or from non-edible oil trees such as Jatropha (*Jatropha curcus* L.*)* and Pongamia (*Pongamia Pinnata* L.). or waste products of the food industry, such as oil used for the production of deep-fried foods. As the name implies, biodiesel can only be used in diesel engines. Ethanol can be used as a substitute for gasoline in flexible fuel vehicles, and is now being offered by many car

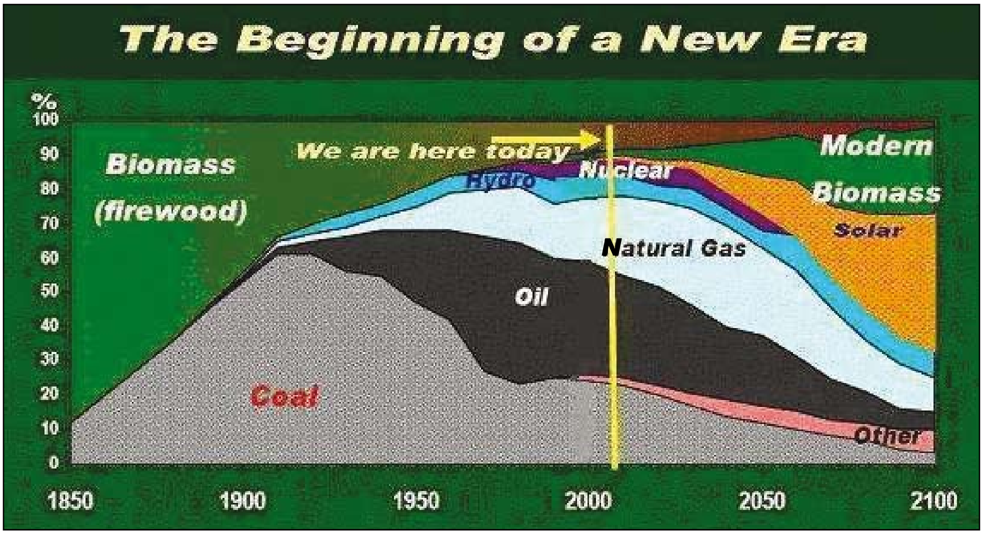

Figure 1. Changes in primary energy shares, 1850 to 2100.
(Source: Nakicenovic et al. (2000) IPCC Special Report on Emission Scenarios).

manufacturers. By 2100, renewable sources of energy (solar, wind and biomass) will provide the major share of energy, replacing the current non-renewable sources of energy such as coal, oil and natural gas (Nakicenovic et al. 2000).

As energy sources such as coal, oil or natural gas are not renewable and are also the primary causes of global warming and environmental damage, all nations will gradually shift their focus to the generation of energy from renewable and environmentally safer sources of energy such as solar radiation, wind, biomass (first, second and third generation biofuels), etc. Biofuels fall under renewable sources of energy, which are contributing a substantial share to the national pools of energy in USA and Brazil. The growth of biofuel industry is phenomenal in recent years in countries like USA, Brazil, Germany, Columbia, Malaysia and China owing to the sharp escalation of crude oil prices in the international markets during the last few years.

Biofuels are currently produced from feedstocks involving conventional food crops such as wheat, maize, sugarcane, palm oil and oilseed rape. Any major switch to biofuels from such crops would create a direct competition with their use for food and feed. The economic consequences of such competition are already being felt in certain parts of the world. Future biofuels are likely to be produced from a much broader range of feedstocks, including the lignocelluloses in dedicated energy crops, such as perennial grasses, and from forestry, the co-products from food production, and domestic vegetable waste. Advances in the conversion processes will almost certainly improve the efficiency and reduce the environmental impact of producing biofuels, from both existing food crops and from lignocellulose sources (Goldemberg 2007).

3. Bioethanol

i) Advantages of bioethanol over other fuels

Ethanol has excellent fuel properties for spark ignition internal combustion engines; for example, its high octane and high heat of vaporization make it more efficient than gasoline (Bailey 1996) and it has a low photochemical reactivity in the atmosphere. Moreover, smog formation from evaporative emissions of pure ethanol can be less than that for gasoline. Ethanol has very low toxicity in comparison to other petroleum-based fuels, and is readily biodegradable in water and soils, reducing penetration of plumes from leaks and consequences of spills.

Former US President George Bush in his ‘State of the Union Speech’ in 2006 declared that the USA would cut 75% of its fuel import by 2025 through biofuel production. Meanwhile, the USA has allocated 375 million dollars for research on biofuel. India’s indicated target states that by 2017, petrol should be blended with 20% bioethanol and diesel with 20% biodiesel. The biofuel law of the Philippines (enacted on 6 May 2006) calls for a 5% mixing of ethanol in gasoline and 1% mixing of biodiesel in petro-diesel during the first two years (2007–2008) of implementation and 10% from the third year to 2011. The countries involved in developing and expanding biofuel industry include Brazil, Columbia, Venezuela, Canada, Thailand, Malaysia, Mozambique, Nigeria and Indonesia.

According to a University of California-Berkeley (USA) study, the production of ethanol reduces petroleum use by 95%, as compared to gasoline refining. Because of ethanol’s 35% oxygen content, ethanol-blended fuel combusts more completely and thus results in lower emissions. The American Lung Association of Metropolitan Chicago credits ethanol-blended fuel with reducing smog formation by 25%. The production and use of ethanol helps reduce carbon dioxide and other greenhouse gas emissions believed to cause global warming. Because ethanol is made from a renewable, plant-based feedstock, the carbon dioxide that is released during fuel combustion is “recycled” by the plant as it grows. The result is a reduction in greenhouse gas emissions by up to 20%. The production and use of 4.9 billion gallons of domestic ethanol reduced CO_2-equivalent greenhouse gas (GHG) emissions by approximately 8 million tons in 2006. That would be the equivalent of removing 1.21 million cars from American roads. (Argonne National Laboratory, GREET 1.7 Model 2007).

The first large-scale schemes for biofuel production began in the early 1970s (eg, in Brazil and the USA), but only recently have biofuels been given notable worldwide consideration as a fossil fuel alternative. Early experiences were mainly motivated by the need to reduce import bills and increase energy security, though laterally rural support appeared as an important driving force. Current high volatility of oil prices mean that the same goals for biofuels are still at the top of the policy agendas, but in addition, new driving forces have emerged, including the potential of biofuels to contribute to mitigating climate change, providing new end-markets and export opportunities for agricultural commodities and even providing alternatives to the illegal production of some crops. The social return of biofuel in energy poor communities is much greater than social return on biofuels used by consumers running their second or third cars.

ii) Global ethanol production

Licht estimates show (Renewable Fuels Association's Ethanol Industry Outlook, 2009) that the top ten producers (in billion litres) of fuel ethanol are USA (34.06), Brazil (24.49), European Union (2.77), China (1.9), Canada (0.9), other countries (0.48), Thailand (0.33), Colombia (0.29), India (0.24) and Australia (0.09). The countries that produce considerable quantities are France, Germany, Spain, Canada, Russia and South Africa. The industry is making rapid strides, particularly in developing countries.

iii) International trade

A few countries dominate production of biofuels for domestic use and export. Bioethanol is still produced in much larger volumes than biodiesel. The US and Brazil are the largest producers of bioethanol. The EU produces almost 95% of the world's biodiesel. Global production of biofuels has increased gradually over time.

The largest increases in production volumes are expected in Brazil, the US, the EU, China, India, Indonesia and Malaysia. The few analyses that have been done based on current production and future policies and targets indicate that annual global production of bioethanol will increase to 120 billion liters by 2020 (IEA 2006). Annual biodiesel production will increase to 12 billion liters by 2020. Recent changes in EU and US policy suggest that these figures are likely to increase by several folds.

Comparing current production trends and targets with different countries' ability to produce biofuels domestically gives an indication of how biofuels trade is likely to develop over the next two decades. In general, existing trade relationships in biofuels are likely to be strengthened with volumes increasing over time. Brazil is currently the largest exporter of bioethanol and has a large capacity to expand its industry to meet domestic and export targets. By 2011, around 20% of Brazilian bioethanol production (5.2 million liters) will be exported. The largest importers are Japan, India and the US, mainly sourcing bioethanol from Brazil (Dufey 2006). Recent initiatives between the US and Brazil suggest that this trade relationship will be strengthened. Brazil has been by far the main exporter (Table 1). Among the countries that have been both exporters and importers, just USA, the Netherlands and Germany were net importers in 2005. Almost 97% of the Brazilian exports in 2005 were as un-denatured ethanol with high degree strength (Licht FO 2006); it is estimated that 96% of the total exports were for fuel ethanol (UNICA 2006). In 2005, Brazil exported ethanol to 47 countries but the bulk of the trade was with just 12 countries (almost 92% of the total volume).

Table 1. Main importers and exporters of ethanol in 2005 (all grades).

Country	Import (%)	Country	Export (%)
USA	18	Brazil	48
Japan	11	USA	6
Netherlands	8	France	6
Germany	8	S. Africa	6
India	8	China	5
UK	6	UK	5
Korea	5	Netherlands	4
France	4	Germany	2
Others	32	Costa Rica	2
		Ukraine	2
		Others	14

(Source: Licht FO 2006).

Japan and South Korea in particular are likely to source bioethanol and biodiesel from Brazil and from Asian countries such as the Philippines, Malaysia and Indonesia. Biodiesel trade is currently limited compared to trade in bioethanol. The most significant increases in trade will most likely be exports from Malaysia and Indonesia to the EU, which has a biofuels target of a 10% blend of biofuels in transport fuel by 2020. Brazil is also developing large-scale biodiesel production from soya oil and plans to export. The US began palm oil-based biodiesel imports from Ecuador in 2005 and these imports are expected to increase rapidly. The biofuel industry is providing substantial employment in US and Brazil while it offers tremendous employment potential either directly or indirectly in other regions as well (Table 2). If second-generation technologies are made commercially viable, this number may increase manifold. The import tariffs are also a concern for the growth of this nascent industry (eg, 2.5% in USA and 186% in India).

Table 2. Employment in biofuels production.

Country	Current (no of people)/additional jobs in the future (no of people)
US (ethanol only)	147,000–200,000
Brazil (ethanol)	500,000
France	25,000 by 2010
Colombia	170,000 by approx 2010
Venezuela	1,000,000 by 2012
China	9,000,000 in the long term
Sub-Saharan Africa	700,000–1,100,000

(Source: Royal society Policy document on Sustainable biofuels: prospects and challenges 2008).

iv) Brazil's success story in biofuels

The alcohol industry in Brazil was initiated and driven by high oil and fluctuating sugar prices. The production of alcohol in Brazil was highly regulated and heavily subsidized until the 1990s. In 1999, alcohol production in Brazil was liberated from government regulation and now enjoys a comfortable resurgence. Progress made in Brazil has been incredible, particularly during the last 30-year period since the initiation of the Brazilian ethanol program—ProÁlcool. Ethanol production has increased 30 times, yield per hectare has increased by 60%, and production costs have declined by 75%. According to Berg (2004), ethanol has been promoted because of its positive net energy balance; that is, the energy contained in a ton of ethanol is greater than the energy used to produce it. Further, Segundo et al. (2005) showed that the low amount of nitrogen fertilizer used by sugarcane, together with technological improvements, has led to an energy balance for sugarcane ethanol of one unit fossil fuel used for eight units biofuel produced. Today, Brazil's bioethanol industry is meeting 30% of the total energy requirement (Nass et al. 2007). The most striking feature of the industry is the integrated approach for future growth being played by scientists, government officials, business leaders and educators. Brazilian sugarcane production was split

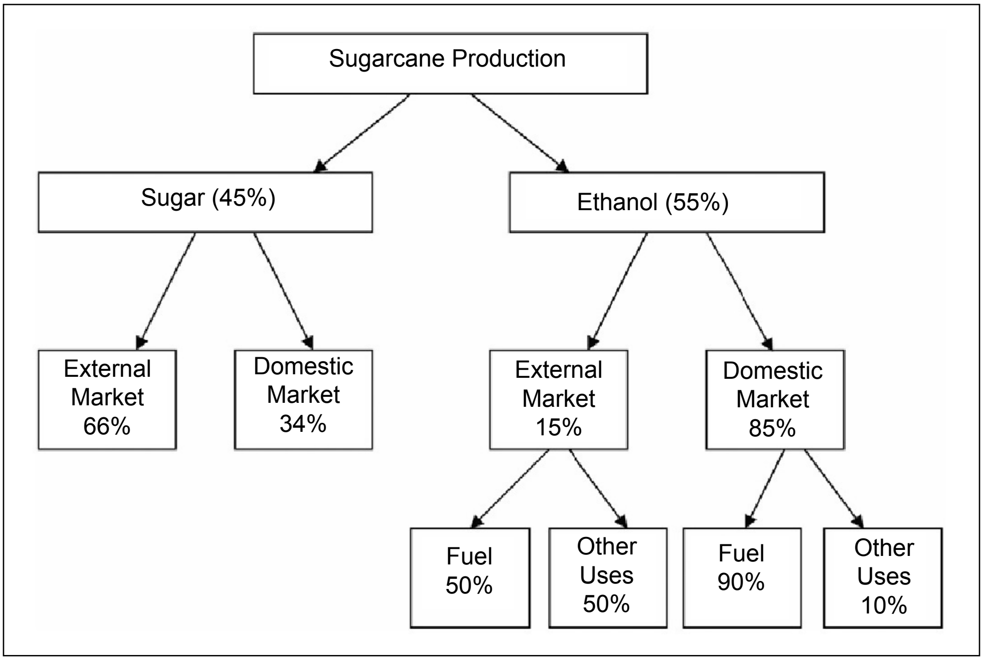

Figure 2. Multiple uses of sugarcane in Brazil 2006.

(Source: UNICA 2007).

almost equally between sugar and ethanol (Figure 2). Nearly 85% of the total ethanol produced is being utilized locally while the rest is exported. Domestic consumption is mainly in the transport sector (90%). This scenario places Brazil to dynamically balance sugar and alcohol production there by influencing of global prices movement of these commodities.

v) Emerging issues/policies

Governments in many countries have initiated or updated existing policies to encourage biofuels. However, policy development is increasingly facing pressure concerning the impact of these policies on food security and their environmental impact particularly on net greenhouse gas (GHG) emissions, land-use changes, water depletion and other environmental issues. The outlook for food, agriculture and energy suggests that the substantial sums spent in Organization for Economic Cooperation and Development (OECD) countries to subsidize the biofuels sector are encouraging rapid investments (OECD 2007). Government supports underpinning the biofuels industry have grown rapidly; it is fair to say that until oil prices began rising rapidly after 2004, biofuels would have been unprofitable without these subsidies, which in 2006 totalled more than 11 billion dollars in the OECD countries (de

Gorter and Just 2008, Steenblik 2007). The US leads this list, with over 6 billion US dollars in annual support (The Energy Independence and Security Act of 2007; P.L.110-140, H.R. mandated production of biofuels to 36 billion gallons by 2022). Blenders are paid a 51 cent-per-gallon "blender's credit" for ethanol, 54 cent-per-gallon tariff on imported ethanol, subsidies for the distribution, storage and transport of biofuels. In the US, 385 million dollars are earmarked to subsidize cellulosic ethanol production in six pilot projects, followed by the EU with about 4.8 billion US dollars (set targets for biofuels at 2% of liquid motor fuel demand in 2005, and at 5.75% by 2010, subsidies to turn surplus low-grade wine into alcohol fuel, 50% tax on imported ethanol). Brazil has also supported this initiative with a variety of direct and indirect subsidies initially (FAO 2008). Many developing countries, such as Angola, Malaysia and Thailand are encouraging ethanol and biodiesel production from sugarcane, oil palm, sugarbeet and cassava.

Maize prices rose 54% from 2004−2006, wheat prices 34%, soybean oil prices 71% and sugar prices 75% in international markets. In 2006-2007, this rate of increase accelerated, according to USDA "due to continued demand for biofuels and drought in major producing countries." Maize prices rose by 28% and wheat prices by 35% during 2007-08. Increased prices coupled with diversion of maize for ethanol production (30% of the corn produce in US) have a drastic impact on food security, which is being felt by the poor in US, let alone the countries in sub-Saharan Africa, South and Southeast Asia and Latin America.

The third issue is the environmental and ecological impacts of growing biofuel crops in vast areas. Expressing concern at the growing expansion of biofuel market, the OECD stated in its Paris summit (OECD 2007) that the production and use of biofuel added no improvement to the environment; it has rather created market instability. Two recent studies focused on the question of carbon loadings and GHG emissions due to land use shifts resulting from biofuels. Fargione et al. (2008) argue that, if land is converted from rainforests, peat lands, savannas or grasslands to produce biofuels, it will immediately incur a "carbon debt". Calculating the savings on greenhouse gas emissions from biofuels compared to fossil fuels, the authors calculate the time in years necessary to repay this debt. In the case of maize for ethanol, this time is 93 years (48 years if grown on "abandoned" cropland); for soybean biodiesel from rainforest it is 319 years; for palm oil biodiesel 423 years on peatland rainforest.

In the light of the urgency of actions to confront global warming, this long "payback" to biofuels is disappointing, suggesting that other measures would be far more effective in facing GHG challenges. Searchinger et al. (2008)

examined how land-use changes for biofuel feedstocks may displace crops previously grown to new areas resulting in further land use conversions. They concluded that conventional feedstocks address inadequately the environmental criteria, especially if cultivation leads to conversion of grassland or forests. Models clearly point to the conclusion that the use of cellulosic feedstocks in second generation biofuels can achieve positive or neutral effects, underscoring the need to move rapidly in this direction.

FAO and governments should undertake technical reviews respecting food security, “subsidy stacking” and the environmental impacts of bioethanol expansion. Especially where assessments are global or transboundary in nature, multilateral review by FAO/OECD, WTO and other groups such as UNEP may be appropriate. It is fundamental that bioethanol policies be reviewed with respect to their classification at WTO, in order to provide guidance and discipline for policy development in a manner that limits transborder policy spillovers, and enables a rational development of the global bioethanol/biofuel industry.

4. Sweet sorghum as biofuel crop

Sweet sorghum [*Sorghum bicolor* (L.) Moench.] produces food (grain) and fuel (ethanol from stem sap) and the stalks contain 10-15 % sugars. The stems are crushed to extract the juice similar to that of sugarcane. Ethanol is produced from sweet sorghum stem juice through fermentation technology as similar with molasses based process using same infrastructure used for sugarcane industry. Further, the juice can be boiled to make sugar syrup with 70–80 %Brix to be used as table syrup (as in USA) or biofuel. But extracting dry sugar from the syrup is the costly process owing to the presence of certain inhibitors such as aconitic acid and starch. Today, sweet sorghum is making its second debut as a highly versatile feedstock that can be used for food, fodder, fuel and animal feed.

i) General advantages of sweet sorghum over other biofuel crops

Sweet sorghum is grown in many countries of Asia, Africa and Americas. Sweet sorghum requires one-fourth the amount of water that sugarcane needs. It has more total sugars (both reducing and non-reducing) in the juice of mature plant than sugarcane. On a comparative time scale, sweet sorghum out-produces sugarcane because of its early maturity (100 to 120 days), while, sugarcane crop takes more than one year to mature. As sweet sorghum requires less water and has a higher fermentable sugar content than sugarcane (which contains more sucrose purity), it is better suited for ethanol production. Also, sweet sorghum-based ethanol is sulfur-free and cleaner than molasses-based ethanol, when mixed with gasoline. Sweet sorghum also may not interfere with food production because it can be grown on less fertile lands and is also drought tolerant.

The ethanol conversion process from sweet sorghum juice generates low or negligible effluents in the spent wash, and the same can be composted with press-mud to produce organic-fertilizer. Sweet sorghum stalk juice can be used successfully for the production of syrup, fuel-grade ethanol, specialty and bulk organic chemicals, industrial alcohol, etc.

Truly, sweet sorghum is a solution to the food-versus-fuel issue. Sweet sorghum has a shorter growth duration and is characterized by very high photosynthetic rate, therefore it can produce more sugar than most other crops on a comparable time scale. 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).

Sweet sorghum is one of the best alternative crops for bioethanol production. It is a food fuel-energy-industrial crop, which requires low water/fertilizer input, has a high yield of grains and biomass (starch/sugars/lignocelluloses) for integrated multi-purpose biorefining, and grows well in marginal lands, in semi-arid and temperate regions, including Africa, Asia, the Americas and Europe. Table 3 gives an overview of the advantages of sweet sorghum as a promising source of ethanol.

Table 3. Characters of sweet sorghum that make it a viable source of ethanol.

As crop	As an ethanol source	As bagasse
• Shorter growth period (3-4 months)	• Eco-friendly process	• Higher biological value
• Dryland crop and less water requiring	• Superior quality	• Rich in micronutrients
• Greater resilience	• Less sulphur	• Use as feed/for power cogeneration/biocompost
• Farmer friendly	• High octane	• Lignocellulosic substrate for ethanol production
• Meets fodder/food needs	• Automobile friendly (up to 25% of ethanol petrol mixture)	
• Non-invasive/least invasive species		
• low soil NO_2/CO_2 emission		
• Propagated by seed		

(Modified from Reddy & Reddy 2003, Reddy et al. 2005 & 2009).

Since ethanol is a “clean burning fuel” with high octane rating due to low sulphates and aldehydes, the existing automobile engines can be operated with Gasohol (petrol blended with ethanol) without any need for engine modification. Sorghum can give high energy return on the fossil energy used to make it while corn only yields 1.3 times the fossil energy used.

The superiority of sweet sorghum over other biofuel crops is vindicated by the following reports. The work of Monti et al. (2007) indicates that sweet sorghum is a rich source of minerals such as calcium (Ca), potassium (K), phosphorous (P) and magnesium (Mg) compared to other biofuel crops such as miscanthus and panicum (Table 4). The sweet sorghum leaves rich in K, Mg and P can be used as fodder for cattle. The reduced quantity of Silicon (Si) in sweet sorghum compared to that of fiber sorghum will aid in palatability of leaves (Si/K is 1.3 in sweet sorghum as against 2.3 in normal sorghum). Low silica content is favorable for fermentation.

Table 4. Ash and mineral concentration in leaves, stems and reproductive organs (Capitulum for Cynara and panicle for sweet and normal sorghum).

Plant Organ	Ash	N	C	Al	Ca	Cl	Fe	K	Mg	Na	P	S	Si	Si/K	Ca/K
Leaves															
Grain sorghum	81	13	424	483	9245	4737	236	8805	3086	195	1246	1105	19736	2.3	1.1
Sweet sorghum	**82**	**14**	**425**	**328**	**8359**	**3741**	**186**	**11661**	**2805**	**189**	**1273**	**1099**	**14858**	**1.3**	**0.7**
Mean	86	11	425	661	10277	6916	330	5307	2367	1903	933	1769	14791	4.4	2.8
Stems															
Grain sorghum	41	2.6	409	114	2643	6398	79	12577	1903	193	702	817	5345	0.4	0.2
Sweet sorghum	**50**	**4.4**	**408**	**152**	**3446**	**7199**	**112**	**12991**	**2079**	**195**	**804**	**681**	**7013**	**0.5**	**0.3**
Mean	37	3.3	423	143	3325	9075	86	6774	1260	2174	571	773	4950	1.0	0.6
Reproductive organs															
Cynara c.	67	14.3	444	106	9960	9863	71	19325	1815	1340	2427	1708	474	0	0.5
Grain sorghum	47	13	434	242	1824	6252	141	5587	2451	192	2150	1084	10671	2	0.3
Sweet sorghum	**58**	**14**	**424**	**218**	**2417**	**5129**	**159**	**7125**	**2895**	**171**	**2620**	**1000**	**14321**	**2**	**0.3**
Mean	57	14	434	189	4734	7081	124	10679	2387	567	2399	1264	8489	1.4	0.4

Ash, N and C are expressed as g kg^{-1} dry matter; the other elements as mg kg^{-1} dry matter. (modified from Monti et al. 2007).

ii) Food-fuel trade-off

It is often stated that sweet sorghum cultivars do not produce grain yield or the grain yield is very less. In the multi-environment trials, sweet sorghum hybrids produced 11% and 38% more stalk and grain yield than varieties suggesting that planting hybrids will give both more food (grain) and biofuel feedstock (stalks) than varieties (AICSIP 2007). Studies at ICRISAT showed that sweet sorghum hybrids had higher stalk sugar yield (by 11%) and higher grain yield (by 5%) compared to grain types, and 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 postrainy season (Table 5). Thus, there is no tradeoff between grain and stalk sugar yields in the sweet sorghum hybrids in the rainy season, while the trade off is minimum in both hybrids and varieties in the postrainy season. This is further supported by the work of Zhao et al. (2009), which states that there is significant soluble sugars in the stems (79-94%) during postanthesis period, the hybrids exhibited significantly high soluble sugars over varieties with same maturity period, and effects of year, harvest time and genotype on calculated ethanol yield (CEY) are highly significant.

Table 5. Trade-off between food and fuel in sweet sorghum varieties and hybrids in different seasons (2005-07).

		Sugar yield (t ha^{-1})			Grain yield (t ha^{-1})		
Season	Variety/ hybrid	Sweet stalks (SS)	Non- sweet stalks	% gain of SS	Sweet stalks (SS)	Non- sweet stalks	% gain/ loss in SS
Rainy season	Varieties	6.0 (6)*	3.9 (11)	54	3.0 (6)	3.3 (11)	-9
	Hybrids	6.2 (5)	5.6 (4)	11	6.2 (5)	5.9 (4)	5
Postrainy season	Varieties	1.7 (11)	0.9 (6)	89	4.6 (11)	4.7 (6)	-2
	Hybrids	1.5 (6)	1.0 (3)	50	6.4 (6)	8.5 (3)	-25

*Numbers in parenthesis indicate number of genotypes used in the study.

(Source: Reddy et al. 2009).

iii) Comparative advantages in cost of production of feedstock

Sweet sorghum scores over sugarcane in terms of water use efficiency (4,000 m^3 vs. 36,000 m^3), fertilizer requirement (100-50−40 kg NPK/ha vs 250 to 400-150-150) and cost of cultivation (US$435 vs $1,079) by many fold compared to sugarcane (Table 6). While, the per day productivity of sorghum is much higher (416.67 kg vs 205.47 kg) than sugarcane. These figures may vary widely with respect to crop management and other factors.

Table 6. Comparative advantages of sweet sorghum vs sugarcane/sugarcane molasses for ethanol production.

Crop	Cost of cultivation (USD ha^{-1})	Crop duration (months)	Fertilizer Requirement per location (N-P-K kg ha^{-1})	Water requirement (m)^3	Ethanol productivity (liters ha^{-1})	Av. stalk yield (t ha^{-1})	Per day productivity (kg ha^{-1})	Cost of ethanol production (USD lit^{-1})
Sweet sorghum	435 over two crops	4	80 – 50 – 40	8000 over two crops	4000 year^{-1} over two crops$^{(a)}$	50	416.67	0.32$^{(d)}$
Sugarcane	1079 crop^{-1}	12-16	250 to 400 –125 -125	36000 crop^{-1}	6500 crop$^{-1(b)}$	75	205.47	
Sugarcane molasses	-	-	-	-	850 year$^{-1(c)}$	-	-	0.37$^{(e)}$

(a) 50 t ha^{-1} millable stalk per crop at 40 l t^{-1}

(b) 85-90 t ha^{-1} millable cane per crop @ 75 l^{-1}

(c) 3.4 t ha^{-1} at 250 l t^{-1}

(d) Sweet sorghum stalk at US$12.2 t^{-1}

(e) Sugarcane molasses at US$39 t^{-1}

(Source: Modified from Rao et al. 2004).

The study undertaken by Rao et al. (2004) at two locations in Andhra Pradesh and Maharashtra, India shows that the cost of production is Rs 17,820 in AP while it is Rs 13,375 in Maharashtra, whereas there is not much difference between the two states for sugarcane (Rs 49,250 vs Rs 48,750). Another study, Rajashekar (2007) compared grain sorghum with sweet sorghum (Table 7), and reported the advantage for sweet sorghum as the farmer can get an additional 133% increase (Rs 5,700 for grain sorghum vs.Rs 13,300 for sweet sorghum) in terms of net returns. This increased returns is due to the absence of any significant grain yield reduction in sweet sorghum. If the same analysis is extrapolated between sweet sorghum and corn or wheat, similar results can be expected as both corn and wheat require more irrigation and intercultural operations, besides requiring a high dose of fertilizer.

Hallam et al. (2001) analyzed the biomass yield and economic potential of several high-yielding annual and perennial crops on prime and marginal or sloping land. Sweet and forage sorghums produced the highest yields at both the locations, Ames and Chariton. Maize often appeared water stressed and had biomass yields that were only 70% of the yields of the sorghums. The costs per ton of the annual sorghum species for biomass (sweet and forage sorghums) are uniformly lower than for any of the perennial crops. At Ames, the lowest cost perennial is switchgrass, ie, \$47.65 t^{-1}, whereas sweet sorghum and forage sorghum are \$38.14 t^{-1} and \$41.81 t^{-1}, respectively. At Chariton, sweet sorghum is only \$32.38 t^{-1}, whereas forage sorghum is \$36.43 t^{-1} and the lowest cost perennial, switchgrass, is \$38.90 t^{-1}. These results are in conformity with those of Rao et al. (2004) and conclusively prove that growing sweet sorghum is economical compared to other annual and perennial energy crops. According to the FAO (Chapman 2002), growing sweet sorghum for grain and stalks in 2002 provided a yearly gross margin of US\$1,300 per ha compared to US\$27 per ha for corn. The data on accrued benefits of sweet sorghum varies widely owing to the management practices, efficiency of juice extraction, stalk yield, etc. The overall picture points to a better position for sweet sorghum in the hierarchy of biofuel crops by means of its high productivity, water use efficiency (WUE), nutrient use efficiency (NUE), returns per unit cost and cost of cultivation.

Table 7. Economics of sweet sorghum cultivation per ha in India (July 2007).

		Grain sorghum		Sweet sorghum	
S. No.	Particulars	Cost (Rs)	Cost (US $)	Cost (Rs)	Cost (US $)
I	**Inputs**				
1	Land preparation	600	14.63	600	14.63
2	Inputs (seed + fertilizers)	3400	82.93	3400	82.93
3	Crop management & harvesting	2800	68.3	3930	78.28
4	Transport & stripping	1000	24.39	2500	36.59
	A) Total cost of cultivation	7800	190.24	10430	254.5
II.	**Outputs**				
1	Grain yield (16 qtls ha^{-1} @ Rs 600/qtl)	12000	292.68	9600	234.2
2	Green stalks 20 tons ha^{-1}@ Rs. 600/ton	1500	36.59	12000	292.8
	B) Total gross returns	13500	329.27	21600	527.0
III.	**Net returns (B-A)**	5700	139.02	13300	324.5
IV.	**B:C ratio (B/A)**	1.73		2.07	

Grain price: Rs 600 qtl^{-1} and stalk price: Rs 600 t^{-1}.

(Source: Rajashekar K 2007).

iv) Comparative advantages in sorganol production

Considering the first generation technologies (crop/fuel chains based on existing technologies – ethanol from sugar/starch) of ethanol extraction, the cost benefit ratio slightly favors sweet sorghum compared to sugarcane. This varies widely from region to region owing to different crop management systems, yield, genotypes, efficiency of juice extraction and fermentation efficiency. A techno-economic feasibility study undertaken by Directorate of Sorghum Research (DSR), formerly National Research Center for Sorghum (NRCS), Hyderabad, Andhra Pradesh indicated that the per liter cost of production of ethanol from sweet sorghum (Rs 13.11) is lower than that from sugarcane molasses (Rs 14.98) (Table 8). In addition to sweet-stalk, an average grain yield of 1.5 to 2.0 t ha^{-1} in rainy season (which can be used as food or feed) can be harvested from sweet sorghum, while the grain yields in postrainy season will be much higher (2.5 to 3.5 t ha^{-1}) than rainy.

Table 8. Comparative per liter cost of ethanol production from sweet sorghum and sugarcane molasses.

Particulars	Sweet sorghum[1] (Rs liter^{-1})	Sugarcane molasses[2] (Rs liter^{-1})
Human power	0.50	0.25
Steam	1.00	1.00
Electricity	1.00	1.00
Yeast	0.10	0.10
Management/Administration	0.10	0.25
Pollution control	Nil	0.25
Raw material	10.41	12.13
Total	13.11	14.98

[1]Sweet sorghum stalk @ Rs 500 t ha^{-1}; [2]Sugarcane molasses @ Rs 2,000 t ha^{-1}.

(Source: Rao et al. 2004).

v) Comparative advantages of stillage/bagasse

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 animals, as it is rich in micronutrients and minerals (Seetharama et al. 2002). It could also be processed as a feed for ruminant animals (Sumantri and Edi Purnomo 1997). The bagasse contains similar levels of cellulose as sugarcane bagasse, therefore has a good prospect as a raw material for pulp products. Blending sweet sorghum juice up to 10% in sugarcane juice does not affect crystallization; therefore, it is compatible with the sugarcane industry. Apart from these, the pollution level in sweet sorghum-based ethanol production has 1/4th biological oxygen dissolved (BOD), ie, 19,500 mg liter^{-1} and lower chemical oxygen dissolved (COD), ie, 38,640 mg liter^{-1} compared to molasses-based ethanol production (Personal communication from Patil, VSI, Pune, India).

Experiments using the bagasse of sweet sorghum or stripped leaves-based feed block (BRSLB) by International Livestock Research Institute (ILRI) and ICRISAT showed that nitrogen content, in vitro digestibility and metabolizable energy (ME) content of the BRSLB were significantly lower than in the commercial sorghum stover-based feed block (CFB), and that the BRSLB was significantly superior to normal sorghum stover but that there were no differences in the neutral detergent fiber (NDF) content (Table 9). As expected, the laboratory quality indices were lowest in the sorghum stover. An important aspect of this experiment was to investigate the palatability of feed blocks when sorghum stover was entirely replaced by BRSLB. There was no (statistical) difference in feed intake between the CFB and the BRSLB (Table 9).

Table 9. Changes in live weight of bulls when fed with different types of diets.

Diets	Nitrogen (%)	NDF (%)	In vitro digestibility (%)	Met.energy (MJ/kg)	Intake (kg/d)	Intake (g/d/kg LW)	Weight changes (kg/d)
CFB	1.81^{a}	56.1^{a}	57.5^{a}	8.21^{a}	7.31^{a}	35^{a}	0.82^{a}
BRSLB	1.65^{b}	56.2^{a}	54.6^{b}	7.77^{b}	7.52^{a}	37^{a}	0.73^{a}
Sorghum stover	0.45^{c}	70.2^{c}	50.5^{b}	7.30^{b}	2.31^{b}	13^{b}	-0.38^{b}

Different superscripts (^{a,b,c}) in a column denote significant differences ($P \leq 0.05$)

NDF - neutral detergent fiber; CFB - commercial sorghum stover-based feed block; BRSLB - experimental sweet sorghum bagasse/stripped leaves based feed block

(Source: Blummel et al. 2009)

5. Sweet sorghum improvement – conventional approaches

i) Sorghum distribution and climatic conditions

Sorghum [*Sorghum bicolor* (L) Moench] is the fourth major cereal crop of 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 system is constrained by poor soils, low and erratic rainfall and low inputs resulting in low productivity. India (9.5 m ha) is the largest sorghum grower in the world followed by Nigeria and Sudan. It 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 (Schaffert and Gourley 1982). The crop can be grown in a wide range of climatic conditions as given below.

Latitude: Sorghum is grown between 40°N and 40°S.

Altitude: Sorghum can be found at elevations between sea level and 1,500 m. Most East African sorghum is grown between the altitudes of 900 to 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 15 to 37^0C and optimum temperature for growth and photosynthesis is 32 to 34^oC, day length: 10 to 14 h, optimum rainfall 550 to 800 mm and relative humidity 15 to 50%.

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

Water: While sorghum will survive with a supply of less than 300 mm rainfall over the season of 100 days, it responds favorably with additional rainfall or irrigation water. Typically, sweet sorghum needs between 500 to 1000 mm of water (rain and/or irrigation) to achieve good yields, ie, 50 to 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 great 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 (about 1.3-1.7 g MJ^{-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.

ii) Constraints to production

Major constraints for sweet sorghum are marginal and poor soils coupled with improper management practices, lack of high yielding genotypes adapted to biotic and abiotic stresses such as *Striga*, shoot fly, stem borer, shoot bug, aphids, anthracnose, grain mold and leaf blight, apart from lodging, drought, salinity, low temperatures, photosensitivity, etc.

The incidence of the above mentioned pests and diseases is bound to aggravate with increased sweet sorghum cultivation especially if serial planting is practiced. Some of the insect pest resistant material developed earlier in ICRISAT (ICSR 93034, ICSV 700 and ICSV 93046) and DSR/AICSIP (CSH22 SS, CSV19 SS and SSV74) was found promising for stalk and sugar yields. It is imperative to screen and develop cultivars for resistance to key insect pests and diseases with improved stalk yields and sugar content.

iii) Critical issues for sweet sorghum

Sweet sorghum is similar to grain sorghum but grows rapidly, and produces higher biomass and has wider adaptation (Reddy et al. 2005). Sweet sorghums are distinct due to their increased sugar content in stalks (Brix 10.0 to 18.0 %) from flowering to maturity than grain sorghum (Brix 9.0 to 11.0 %) during the same period (Anonymous 2008). As sweet sorghum gives reasonable grain yield in addition to juice with high total soluble sugars, food security is not undermined in developing countries. The majority of the constraints for the growth and production of sweet sorghum are similar to that of grain sorghum. The following critical issues were observed mostly based on the research experience at DSR, AICSIP and ICRISAT.

1. G×E interactions are significant for sweet sorghum related traits; the genotypes that perform well in the rainy season are not necessarily the top-performers in the postrainy season and *vice versa.* Preliminary results indicate that non-allelic interactions are more predominant for stalk sugar and allied traits.
2. The major constraints include the non-availability of required quantity of feedstock continuously during the time suited to the crushing period of Industry other than sugarcane season.

3. The postrainy (*rabi* crop in India) season grown (Oct-Nov planted) crops will give 30-35% less stalk yield with reduced sugar content than rainy (*kharif* and summer in India) ones because of short daylength, low night temperatures, and radiation.
4. In order to meet the Industry demand for raw materials especially after crushing of sugarcane crop, there is a need to develop sweet sorghum cultivars that are photo-and thermo-insensitive adapted to postrainy season with high stalk and sugar yields.
5. Experiments on sweet sorghum adaptation in distilleries/sugar factory operational areas especially on staggered planting in different seasons are urgently needed to meet the continuous supply of feedstock.
6. Introduction of sweet sorghum to new area is likely to be easier and successful between regions with the same latitude. It may result in great loss if a disease or pest is brought in with an introduction from another country. New varieties should be officially introduced through quarantine to avoid problems. It is high risk to introduce a large amount of seeds at one time without prior testing. Initial farm trials are needed before planting the sweet sorghum in a large area.
7. The main economic product is the sugar content in the stalk. Therefore, the selection of cultivars with high sugar content is desirable. If the intention is to use the crop for sugar (sucrose), the cultivars selection should be having high sugar content; and less starch and aconitic acid. On the other hand, if the juice is processed for alcohol, the high amount of reducing sugar and starch do not matter because all can be used as materials for fermentation.
8. A large difference in temperature between day and night, during post flowering period favors the accumulation of sugar in the stalk and nutrients in the seed.
9. As global climate is so gradually changing to higher temperatures and sweet sorghum is bound to grow in new areas, thermo- photo insensitive non-lodging cultivars that are resistant to multiple pests and diseases need to be developed.
10. Need for breeding of short, mid-late and late maturing genotypes to have a broad harvest window in sweet sorghum, thereby providing raw material to the distillery over a long period. Proper planning of sowing of a mix of these cultivars in the catchment area of the distillery would help to achieve more commercial stalk sugar/ethanol.
11. When cultivars with different maturity groups are grown in an area, pests such as shootfly, stem borer, aphids, midge, etc, are likely to

infest late maturing cultivars. Therefore, breed for tolerant cultivars for these insects.

12. Sorghum crop is traditionally challenged by marginal lands with poor fertility status and moisture holding capacity. Sweet sorghum too encounters similar problems. At times, water inundation due to excessive rains/floods also becomes an unforeseen constraint.

Rajendran et al. (2000) reported that deheading treatment resulted in significant increases in millable stalk and sugar yields over those of the intact control plants. As a result of panicle removal, stem dry matter accumulation increased and side tillers were generated. The amount of juice extracted increased in the treated plants, but sucrose (Pol. percentage), %Brix and purity levels in the juice were reduced in comparison with the intact plants. This needs to be confirmed using multi-year multi-location trials (MYMLT).

The self fermentation of juice inside the stalk prior to juice extraction is a major concern (if juice extraction is delayed after harvest due to long distance between factory and the field). Preliminary results indicated that there will be a reduction of sugar yield by 16.8% if the juice extraction is delayed by 48 hours (Reddy et al. unpublished). Research should address the post-harvest losses in terms of juice quality and quantity.

iv) Traits and their associations

Sweet sorghum improvement should aim 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 and its components. Ganesh et al. (1995) showed a significant positive correlation between girth of the stem, cane yield, juice yield, %Brix, total sugars and sucrose %, and alcohol yield. Among these, the total sugars recorded the highest correlation (0.805; $P \leq 0.01$) with alcohol yield followed by sucrose percent (0.783; $P \leq 0.01$), %Brix (0.605; $P \leq 0.05$), juice yield per plant (0.745; $P \leq 0.05$), stalk yield per plant (0.746; $P \leq 0.05$) and girth of the stem (0.360). Therefore, the conventional breeding approaches invariably encompass the component traits of sucrose yield as single trait such as stalk sugar improvement alone may not yield desired results. Seetharama et al. (1987) and Tsuchihashi and Goto (2004) have reported the high positive correlation between %Brix values and total sugars in the juice ($r = 0.95$; $p \leq 0.01$). Fresh stalk yield had shown very high significant positive correlation with fresh biomass and juice yields (0.803 & 0.842 res.; $p \leq 0.01$.) indicating that a very high fresh stalk yield is prerequisite for higher biomass and juice yields in sweet sorghum (AICSIP 2006, 2007).

In a mutli-environment study, %Brix content has shown very strong positive correlations with sucrose content, and total soluble sugars (0.897, and 0.892

res.; p≤0.01) suggesting that %Brix could be used as surrogate trait for measuring sucrose and total sugars in screening large number of breeding materials and segregating populations (AICSIP 2007). Further more, both total sugar yields and computed ethanol yields were positively related (0.996; p≤0.01) indicating that greater sugar yields are essential to realize high ethanol yields in sweet sorghum (AICSIP 2006, 2007). AICSIP (2008) has reported that juice yield was significantly and positively correlated with fresh stalk yield (0.813; p≤0.01), juice extraction (0.731; p≤0.05) and grain yield (0.604; p≤0.05). Highly significant and positive associations were observed by Mallikarjun et al. (1998) between the available sugar and other quality parameters and also among themselves. Available sugar percentage was significantly and positively associated with pol percentage, %Brix, reducing sugar content, non reducing sugar content, pH and specific gravity. Patil et al. (1995) found the juice yield percentage, panicle length, numbers of primary and secondary branches, and test weight to be significantly and positively correlated with grain yield both at genotypic and phenotypic levels. This is further supported by the data from the studies at ICRISAT.

The genetic and regression studies using a large number of genotypes over rainy and postrainy seasons for two years indicated that an increase in cane yield, juice yield, %Brix and plant height had a linear increase in sugar yield in the B/A (B line is maintainer line crossed with a male sterile A-line for seed multiplication of female line) and R-lines (R-line is a restorer male fertile line that is crossed with A-line to produce heterotic hybrids). In hybrids, non-additive gene action plays a significant role for sugar yield, juice yield and cane yield for which high heterosis was also noted (Meshram et al. 2005 and Rajashekhar 2007). Studies on ICRISAT bred material of 9 females and 16 restorers showed that significant positive general combining ability (GCA) effects for plant height were highest in ICSB474 (17), cane weight in ICSB77 (142), juice weight and juice volume in ICSB77 (48). Similarly, specific combining ability (SCA) studies on 144 hybrids revealed that SCA effect was maximum for: plant height in (ICSA474 × ICSR 196 (68%); for cane weight in ICSA264 × SSV84 (148%); juice weight in ICSA404 × GD65122 (43%) (Rajashekar 2007). Heterosis for high %Brix was not observed in hybrids (low Brix is partially dominant); so it is imperative to exploit sca for hybrids. Maximum proportion of variation for sugar yield in hybrid parents and hybrids is due to genetic factors (broad sense heritability).

v) Genetic variability for stalk and sugar traits

There is no dearth of genetic variability for stalk sugar traits (%Brix, juice volume and cane biomass) among varieties/restorers and female (A/B lines) parents. %Brix ranged from 12 to 24% in the rainy season and 9 to 19% in the postrainy season in R-lines/ varieties and from 10 to 15% in the rainy season and 8 to 13% in the postrainy season among the 600 A/B pairs screened at ICRISAT-Patancheru. Germplasm from West and Central Africa (WCA) and Eastern and Southern Africa (ESA) believed to have high sugar yield per unit area are under evaluation at ICRISAT. The wide range of variability for %Brix (from 13 to 24), sucrose% (from 7.2–15.5), stalk yield (from 24 to 120 t ha^{-1}), biomass yield (from 36 to 140 t ha^{-1}) and grain yield (from 1.5 to 7.5 t ha^{-1}) in sweet sorghum (Almodares et al. 1997) indicates good scope for selection of sweet sorghum lines with high sweet-stalk yield coupled with high sucrose %.

The stalk yield of sweet sorghum ranged from 29.4 to 46.5t ha^{-1} with a mean of 40.2 t ha^{-1} across 14 locations (AICSIP 2007). Genetic differences for fresh millable stalk yield in the range 22.0-46.5 t ha^{-1} were reported by Singh and Singh (1986), Bapat et al. (1986), Seetharama et al. (1987), Balaravi et al. (1997a), Channappagoudar et al. (2007), and Woods (2001) in the tropical climatic conditions, while Almodares et al. (2008) have reported significant differences in fresh stalk yield (range 53-72 t ha^{-1}) at physiological maturity in a set of cultivars and lines in Iran. On the other hand, stalk yields reported from the temperate climatic conditions (range 50-90 t ha^{-1}) were much higher than that of tropical climates (Smith and Buxton 1993, Murray et al. 2008a)

Juice brix recorded at physiological maturity varied significantly between 15.8 and 19.6% with a mean of 16.8%. Among the test varieties, SPSSV 30 (19.6%) alone recorded significantly superior %Brix than check SSV84 (AICSIP 2007). Significant genotypic variability in juice brix among the sweet sorghum cultivars were also reported by Singh and Singh (1986), Almodares et al. (1997) and Channappagoudar et al. (2007). Total Sugar yields among sixteen cultivars tested across 14 locations in a tropical climate varied between 1.66 and 2.53 t ha^{-1} with a mean of 1.99 t ha^{-1} (AICSIP 2007). Interestingly, the total sugar yields reported from temperate climatic conditions were higher than tropical and are in the range of 4.0-10.7 t ha^{-1} (Ferraris 1981, Smith and Buxton 1993, Tew et al. 2008).

Genotypic differences for extractable juice, total sugar content, and fermentation efficiency and alcohol production have also been reported (Ratnavathi et al. 2003). Significant difference in computed bioethanol yields (range: 925 to 1440 L ha^{-1}) was observed in the multi-environment and multi-year trials under tropical climate (AICSIP 2006 and 2007). While, the computed bioethanol yields reported from temperate climatic conditions were much higher than tropical and are in the range of 2129 to 5696 L ha^{-1} (Monk et al. 1984, Woods 2001 and Tew et al. 2008). During summer 2000, the

%Brix in the available sweet stalked B lines was studied at DSR, Hyderabad, India and the range was observed to be from 8.3-20.0%.

F_2 population of many experimental crosses showed a continuous variation for stalk sugar content and genotypes with high stalk sugar content could be selected in the segregating generations. The range of standard heterosis for days to 50% flowering, stem thickness, %Brix, plant height and hundred grain weight were narrow. But, it was highest for cane weight in ICSA77 × ICSV 574 (145%), juice weight in ICSA77 × ICSV 574 (435%), juice volume in ICSA77 × ICSV 574 (437%), ear head weight in ICSA657 × SSV74 (142%) and grain yield in ICSA 657 × SSV74 (232%) (Rajashekar 2007). The predominant role of non-additive gene action for plant height, stem girth, total soluble solids, millable sweet-stalk yield and extractable juice yield (Sankarapandian et al. 1994) indicates the importance of heterosis breeding for improving these traits. The substantial magnitude of standard heterosis for all the traits related to ethanol production (plant height: up to 46.9%, stem girth: up to 5.3%, total soluble solids (%): up to 7.4%, millable stalk yield: up to 1.5% and extractable juice yield: up to 122.6%) (Sankarapandian et al. 1994, Ganesh et al. 1996). These results are in conformity with those from ICRISAT and suggest heterosis breeding for genetic enhancement of sweet sorghum.

vi) Progress in breeding

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 (NARI, Website: www. nariphaltan.org/nari, Rajavanshi and Nimbkar 1996). The first major attempt in India was made at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) to evaluate and identify useful high biomass producing sweet sorghum germplasm from world collections (Seetharama et al. 1987). The sweet sorghum improvement program during last two decades at National Research Centre for Sorghum (now DSR) and All India Coordinated Sorghum Improvement Project (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) with productivity ranging from 40–50 t ha^{-1} (AICSIP 2004, 2005, 2006, 2007, 2008). ICRISAT, Patancheru, India has developed a number of sweet sorghum breeding materials, experimental varieties and hybrids having high stalk sugar content and grain yields (Reddy et al. 2005). In several multi-environment trials in India, cv SSV 84 has consistently yielded an average 37.5 t ha^{-1} of stalk yield with a stable %Brix of 18.6% (Balaravi et al. 1997b).

Pedigree method of breeding is being widely practiced for varietal development while parents with high GCA for high sugar yield and %Brix are crossed in developing heterotic hybrids. Recurrent selection program, employing ms_3 gene-populations can be used for the development of restorer and maintainer lines.

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. A few of these cultivars have been released by DSR and AICSIP, for example, varieties SSV84, CSV 19SS, SSV74, SPSSV6, SPSSV11 and hybrid CSH22SS are under commercial cultivation. ICRISAT, along with its partners, 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, Mali and Uganda. High sugar yielding varieties/restorers SPV 913 (NTJ2), SPSSV30, SPV 422, Serado, ICSR 93034, S35, ICSV 700, ICSV 93046, ICSV 25263, SP 4487-3, SP 4484-1, SP 4484-3, SP 4482-1, SP 4482-2 and SP 4481-1, and promising hybrid parents ICSB 264, ICSB 293, ICSB 321, ICSB 401, ICSB 405, ICSB 472, ICSB 474, ICSB 722 and ICSB 729 were identified. Varieties are more photoperiod sensitive than hybrids and the latter are mid-late and have significant heterosis (30–40%) for cane, juice and sugar yields than former. A sweet sorghum hybrid, CSH22SS (NSSH104), developed by DSR Hyderabad and AICSIP centers, India using ICSA 38, an ICRISAT-bred male sterile line and SSV 84 as a restorer, was released for commercial cultivation in 2005. Some of the promising hybrids identified and under advanced testing include ICSSH 3, ICSSH 19, ICSSH 22, ICSSH 23 and ICSSH 28.

Studies were conducted at ICRISAT, DSR and elsewhere to understand the inheritance of extractable juice, total sugar content, fermentation efficiency and alcohol production in sweet sorghum. The evaluation of four promising sweet sorghum lines [Keller, BJ 248, Wray (varieties) and NSSH 104 (hybrid)] along with the check SSV 84 indicated substantial genotypic differences for extractable juice, total sugar content, fermentation efficiency and alcohol production (Ratnavathi et al. 2003). An analysis of 53 ICRISAT-bred elite hybrids in both the rainy and postrainy seasons (Table 10) showed that the correlation and regression coefficients are significantly high for all the component traits of sugar yield (%Brix, stalk yield, juice weight and juice volume). The heritability for plant height, flowering time and one thousand seed weight was high (Brown et al. 2006, Ritter et al. 2007, Murray et al. 2008a and Table 10), while calculated traits like stem juiciness, sugar concentration in stems, total sugar, juice glucose, juice fructose and juice sucrose had low heritability (Murray 2008a and Table 10). The seasonal variations for correlation, regression and heritability are considerable in magnitude and in the same direction.

At DSR, Hyderabad, India, Generation mean analysis of two crosses has showed predominant additive gene action for traits like sucrose and %Brix in stalk juice. However, for cane and juice yield, dominance gene action and dominance x dominance gene interaction were of higher magnitude in both the crosses. Since the traits important for high sugar content are having dominance and over-dominance inheritance, utilization of hybrid vigor by developing sweet sorghum hybrids is an attractive option. Also one of the parents with high sucrose content will suffice in getting good hybrids with high sugar and juice yield (AICSIP 2007).

Table 10. Season-wise correlation, regression and heritability of sugar yield component traits.

S.No.	Trait	Correlation coefficient in rainy season 2008	Correlation coefficient in postrainy season 2008	Regression coefficient in rainy season 2008	Regression coefficient in postrainy season 2008	Heritability in rainy season 2008	Heritability in postrainy season 2008
1	Days to 50% flowering	0.42**	0.48**	0.17	0.23	0.80	0.88
2	Plant height (m)	0.39**	0.59**	0.15	0.35	0.58	0.83
3	Girth (mm)	0.52**	0.45**	0.27	0.20	0.35	0.18
4	Stalk weight (t ha^{-1})	0.86**	0.88**	0.74	0.77	0.59	0.45
5	Cane weight (t ha^{-1})	0.84**	0.88**	0.71	0.77	0.61	0.47
6	Juice weight (t ha^{-1})	0.96**	0.82**	0.93	0.68	0.46	0.39
7	Juice volume (kl ha^{-1})	0.95**	0.78**	0.90	0.61	0.41	0.34
8	Bagasse (t ha^{-1})	0.57**	0.88**	0.26	0.78	0.44	0.52
9	%Brix	0.14	0.62**	0.02	0.39	0.20	0.49
10	Grain yield (t ha^{-1})	0.18	-0.31*	0.03	0.10	0.19	0.41
11	Sugar yield (t ha^{-1})	-					
	-	-	-	0.39	0.51		

(** significant at $P \leq 0.01$; * significant at $P \leq 0.05$)

The predominant role of non-additive gene action for plant height, stem girth, total soluble solids, millable stalk yield and extractable juice yield, substantial magnitude of standard heterosis for all the traits related to ethanol production (stem girth: up to 5.3%, total soluble solids%: up to 7.4%, millable stalk yield: up to 1.5% and extractable juice yield: up to 122.6%) indicates the importance of heterosis breeding for improving these traits (Sankarapandian et al. 1994). The significant positive correlation of general combining ability effects with *per se* performance of parents in sweet sorghum facilitates quicker identification and development of sugar rich, high biomass yielding hybrid parents (Selvi and Palanisamy 1990).

From these studies, it is quite evident that the traits are governed by multiple genes and both additive and dominance components of gene action have to be exploited while breeding for high stalk sugar and juice yielding genotypes. Under these conditions, mapping of QTL contributing to the traits will be very useful in selecting the desired genotypes from huge populations and enhance the pace of development of stabilized improved lines.

Further improvement in %Brix, juice volume and stalk yield (≥ 45 t ha^{-1} with hybrids) should be targeted in sweet sorghum to help improve the benefits to the industry and farmers without any detrimental effect on grain yield. The juice volume should not be compromised while increasing the %Brix. The best way of selecting genotypes will be based on sugar yield per ha (a function of juice yield and %Brix) with 16–19% Brix as the base level in the restorers and 10 to 15% in the female parents in the rainy season, and 9 to 17% in R-lines/varieties and 8 to 13% in the female parents in the postrainy season. Going by the high variability present in sorghum germplasm for %Brix (up to 23%) with a low %Brix observed in female (seed) parents (12–15%), there is an urgent need to improve the sugar content (%Brix) in seed parents through genetic enhancement.

vii) G×E interactions

It is imperative to have stably performing cultivars (varieties or hybrids) across locations, seasons and years to realize higher stalk sugar or grain yields. The interaction of genotype with the environment has an important bearing in breeding improved varieties. G×E interaction has a masking effect on the performance of a genotype and hence the relative ranking of the genotypes do not remain the same over different environments. Adaptability of genotypes to environmental fluctuations is important for the stabilization of crop production over regions, seasons and years. Several methods such as regression analysis, multivariate clustering analysis, multiplicative formulations such as additive main effects and multiplicative interaction besides nonparametric methods may be used for the G×E interaction. Among all, the Eberhart and Russell (1966) model is widely used for stability parameters. The genotypes with high mean, regression coefficient (bi) close to unity and less/no deviation from regression (S^2_{di}) are found to be stable. The improved sweet sorghum varieties and hybrids were evaluated during 2005–07 in both the rainy and postrainy seasons. The data presented in Table 11 clearly shows that there is significant interaction of genotypes with seasons and years for TSS, sugar yield and grain yield in varieties/restorer lines as well as in hybrids. Mean squares due to genotype × year × season interaction for the three traits showed differential behavior of genotypes in different seasons and years except for sugar yield in hybrids.

Table 11. Combined ANOVA of sweet sorghum hybrids and R-lines evaluated over two seasons (rainy and postrainy) and three years (2005-07) for sugar and grain yield.

	Hybrids			R-lines/varieties		
Source of variation	Total soluble solids %	Sugar yield (t ha^{-1})	Grain yield	Total soluble solids % (t ha^{-1})	Sugar yield (t ha^{-1})	Grain yield (t ha^{-1})
Year	175.29**	55.35**	140.72**	162.58**	22.49**	552.79**
Residual	4.93	1.27	0.74	0.73	1.4	2.73
Season	1077.70**	957.97**	163.91**	804.60**	900.99**	244.59**
Year × Season	77.29**	12.45**	178.74**	515.21**	3.54	317.34**
Residual	2.18	0.59	5.33	0.73	1.4	2.73
Genotype	17.06**	3.98**	16.72**	39.08**	9.77**	6.43**
Year × Genotype	8.13**	1.18	10.65**	6.21**	1.77**	5.95**
Season × Genotype	18.83**	2.21**	21.26**	23.24**	6.48**	6.86**
Year × Season × Genotype	8.53**	1.41	8.34**	8.27**	1.55**	4.05**
Residual	2.29	0.9	1.99	1.92	0.44	1.01

(** significant at $P \leq 0.01$; * significant at $P \leq 0.05$)

The mean, regression coefficient (bi) and deviation from regression (S^2_{di}) for some of the stable performing hybrids in rainy and postrainy seasons is given in Table 12. The high sugar and grain yielding hybrids have *bi* more than unity, indicating that these genotypes perform better under favorable environments for grain yield and sugar yield in rainy season. Surprisingly, in the post rainy season, most of the improved hybrids have *bi* less than unity, indicating that these genotypes perform better under unfavorable environments like drought, salt stress and low temperature stress.

Table 12. Mean and stability parameters for sugar and grain yield of sweet sorghum.

	Total soluble solids %			Sugar yield ($t\ ha^{-1}$)			Grain yield ($t\ ha^{-1}$)		
Hybrid	Mean	bi	S^2_{di}	Mean	Bi	S^2_{di}	Mean	bi	S^2_{di}
Rainy season									
ICSSH 30 (ICSA 724 × SSV 74)	16.3	1.61	-0.72	6.0	1.08	0.43	7.0	1.10	2.89
ICSSH 24 (ICSA 675 × SPV 422)	17.3	0.43	-0.82	6.7	1.21	-0.27	4.7	1.68	4.41
ICSSH 21 (ICSA 38 × NTJ2)	15.4	1.14	-0.65	6.0	1.21	-0.63	5.9	1.20	-0.11
ICSSH 57 (ICSA 474 × ICSR 93034)	15.5	1.39	-0.87	5.9	1.19	-0.66	7.2	0.94	-0.06
CSH 22SS (check)	18.3	0.13	-0.82	5.8	0.06	-0.14	3.0	0.78	-0.44
Postrainy season									
ICSSH 28 (ICSA 474 × SSV 74)	12.3	0.5	-0.5	1.6	1.0	0.2	7.4	0.5	-0.9
ICSA 702 × SSV 74	12.3	1.6	-0.1	1.4	1.3	-0.1	6.4	0.2	-1.0
ICSSH 57 (ICSA 474 × ICSR 93034)	12.8	-0.1	-1.2	1.5	0.6	0.2	6.1	-0.4	2.3
ICSSH 26 (ICSA 749 × SSV 74)	11.6	1.3	-0.7	1.7	2.1	0.4	6.9	-1.1	-1.1
CSH 22SS (check)	11.6	0.4	0.9	1.3	0.6	0.0	9.0	1.4	3.1

GGE biplot analysis has evolved into a comprehensive analysis system whereby most questions that may be asked pertaining to a genotype are graphically addressed (Yan 2001, Yan et al. 2007). The genotype main effect plus genotype by-environment interaction (GGE) analysis of the above data further gave finer details on principal components 1 and 2 explaining more than 80% of the interaction for both the traits (Figure 3, a&b). The graphical representation of the G×E in biplots helps in easy identification of best performing adapted genotypes as judged based on position on vertex and the position with reference to the seasonal vectors giving information on magnitude and direction of interaction. (Yan and Kang 2003). Based on the above biplots, we can conclude that ICSSH 24 and ICSSH 30 are best suited for the rainy season while ICSSH 39 and 28 are best for sugar yield. ICSSH 30 is suited for both the seasons for grain yield.

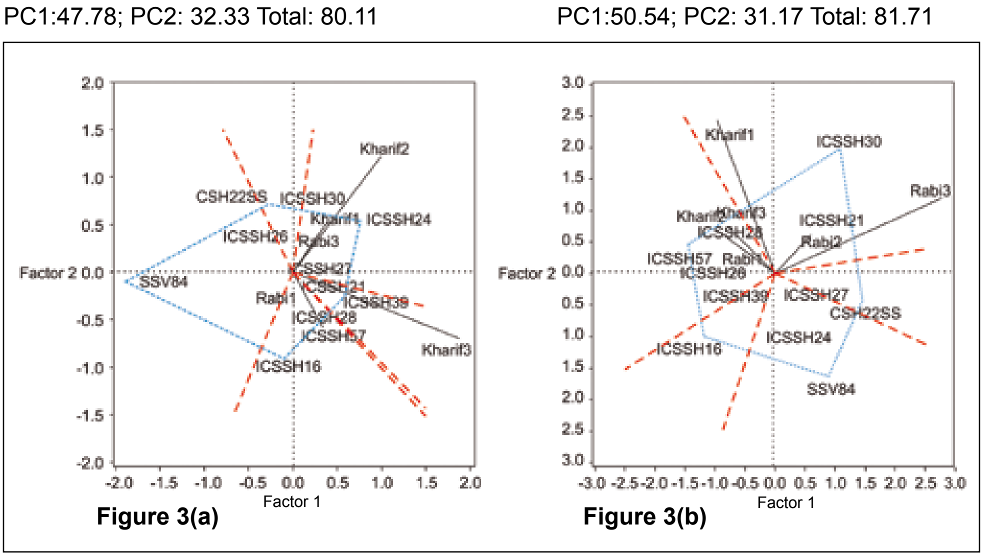

Figure 3 (a&b). GGE biplot analysis (which-won-where view) of sugar yield and grain yield.

viii) Promising/released cultivars

Some of the released/promising cultivars from ICRISAT/national program in India and also from USA and Brazil are shown below (Table 13) and Figure 4.

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. (Zhu Cuiyun 1998). Dale, Theis, Cowley, Tracey, BJ 248 and sugardrip are some of the other sweet sorghum varieties grown all over the world.

ix) Sorghum as a biomass crop

With the development of biocatalysts including genetically engineered enzymes, yeasts and bacteria, it is possible to produce ethanol from lignocellulosic biomass, including cereal crop residues (stovers). Currently, a few countries with higher ethanol and fuel prices are producing ethanol from ligno-cellulosic feedstocks (Badger 2002).The present day sweet sorghum hybrids/varieties, on an average, yield about 3-5 t ha^{-1} of grain and 50-80 t ha^{-1} of biomass per hectare. The other biomass crops such as banana grass and miscanthus also yield above 50 t ha^{-1}, while a highly invasive species like water hyacinth gives much higher yields (Figure 5).

Table 13. Promising sweet sorghum cultivars (hybrids/varieties).

Hybrid/ variety	AICSIP tested no.	Pedigree	Days to 50% flowering	Plant height (m)	Millable stalk yield (t ha^{-1})	Juice yield (kl ha^{-1})	Grain yield (t ha^{-1})	Sugar yield (t a^{-1})	Remarks
ICSV 93046	SPSSV 20	Pedigree selection from the cross ICSV 700 × ICSV 708	87	3.1	43.1	14.9	1.18	2.04	Developed at ICRISAT and has completed advanced testing in AICSIP trials and submitted for release. The variety is tolerant to shoot fly, stem borer and leaf diseases. It ratoons well and has staygreen stems and leaves even after physiological maturity. This variety has performed very well in the Philippines yielding 3.4 - 4.1 t ha^{-1} grain yield/ha while the biomass yield was 50 t ha^{-1} in both main and ratoon crops.
NTJ 2	SPV 913	Pure line selection from E-1966, a zera zera landrace	90	2.9	34.7	10.4	0.95	1.64	The variety has excellent fodder quality when grown in rainy season. It is resistant to leaf diseases. It was released in Andhra Pradesh State in 1990 as Nandyala Tella jonna by ANGRAU for grain purpose in rabi.

...Continued

Table 13. *Continued*

Hybrid/ variety	AICSIP tested no.	Pedigree	Days to 50% flowering	Plant height (m)	Millable stalk yield (t ha^{-1})	Juice yield (kl ha^{-1})	Grain yield (t ha^{-1})	Sugar yield (t ha^{-1})	Remarks
SPV 422	SPV 422	Derived from good grain population	93	3.3	38.3	8.6	0.83	1.40	The variety is resistant to leaf diseases.
CSH 22SS	NSSH104	ICSA 38 × SSV 84	82	3.5	46.5	16.3	1.60	2.14	Developed at DSR, Rajendranagar, Hyderabad, released for cultivation in India in 2005. Jaggery has confectionery taste.
ICSSH 21	SPSSH24	ICSA 38 × NTJ 2	78	3.3	33.2	8.0	1.55	1.28	Developed at ICRISAT and is in advanced testing in All India Coordinated Sorghum Improvement Project Trials-2009.
ICSSH 58	SPSSH30	ICSA 731 × ICSV 93046	80	3.6	42.8	17.7	2.54	1.60	Developed at ICRISAT and is in advanced testing in AICSIP trials-2009.
CSV19 SS (RSSV9)	RSSV9	RSSV 2 × SPV 462	78	3.3	36.8	13.0	1.23	1.59	Developed at AICSIP, Rahuri, Maharashtra, India. Released for cultivation in India in 2005 as CSV 19SS. The variety has tan plant color, purple coleoptiles, dull green midrib, pearly white medium seed and is tolerant to shootfly.

...Continued

Table 13. *Continued*

Hybrid/ variety	AICSIP tested no.	Pedigree	Days to 50% flowering	Plant height (m)	Millable stalk yield (t ha^{-1})	Juice yield (kl ha^{-1})	Grain yield (t ha^{-1})	Sugar yield (t ha^{-1})	Remarks
SSV84	SSV84		84	2.8	35.6	12.4	1.29	1.66	It is the first sweet sorghum variety developed by AICSIP, Rahuri in 1992.
SSV 74	SSV74		76	3.6	40.5	16.8	2.12	2.77	It is the sweet sorghum-cum-forage variety released by UAS, Dharwad.
Keller		Mer 50-1 × Rio			49.8	19.1*			High sucrose, low reducing sugars containing line developed in USA.
Wray					49	18.5*			High sucrose, low reducing sugars containing line introduced from South Africa to USA.
Rio		MN 1048 × Rex			47.4	17.5*			High sucrose, low reducing sugars containing line developed in USA.
M-81 E									Late maturing line suitable for syrup making with high reducing sugars.
Brandes									Late maturing line suitable for syrup making with high reducing sugars.

...Continued

Table 13. *Continued*

Hybrid/ variety	AICSIP tested no.	Pedigree	Days to 50% flowering	Plant height (m)	Millable stalk yield (t ha^{-1})	Juice yield (kl ha^{-1})	Grain yield (t ha^{-1})	Sugar yield (t ha^{-1})	Remarks
CMX631		BW-187-2-1-C-C-C	72	3.05	40-60	16-21*			Developed at Embrapa, Brazil
CMSxS642		RW-20-4-2-C-C-C	66	3.10	40-60	16-21*			Developed at Embrapa, Brazil
BR505		Wray Selection	66	2.85	48.6	16-21*			Developed at Embrapa, Brazil

* %Brix only.
(Source: AICSIP sweet sorghum annual reports 2004-2008; Personnel communication from Robert Schaffert, Embrapa, Brazil and Pederson J, USDA-ARS)

Figure 4. The first sweet sorghum hybrid released in India - CSH 22SS and a promising shoot fly tolerant sweet sorghum variety - ICSV 93046.

a) Strengths

Sorghum possesses great genetic diversity for high biomass production, and has a high tolerance to abiotic stresses such as drought and heat besides other positive traits discussed in the earlier sections. Also, sorghum root mass contributes to the build-up of soil organic carbon after removal of the aerial parts of the plant, and would thus alleviate

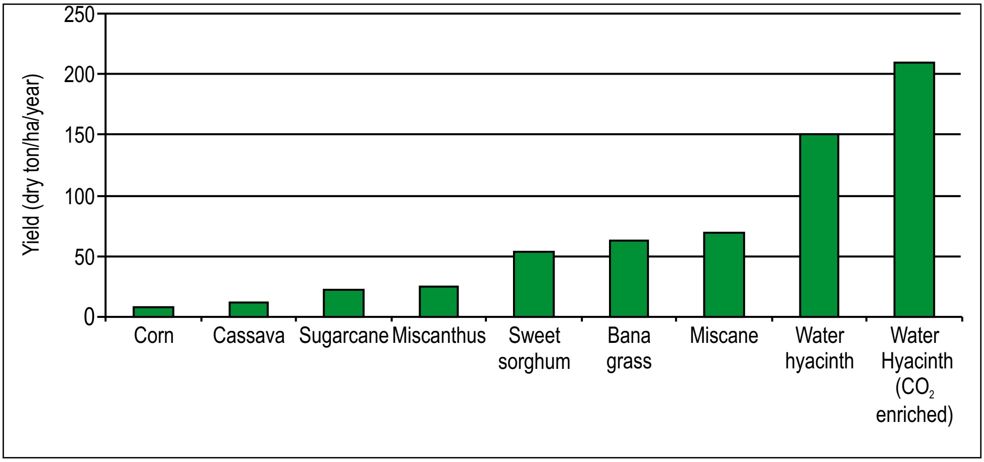

Figure 5. Dry matter production potential of various biomass crops. (Adopted from Texas A&M University, College Station, USA).

concerns about depletion of soil organic matter resulting from the removal of stover (Wilhelm et al. 2004) at least partly. Therefore, sorghum stover serves as an excellent feedstock for lignocellulosic ethanol production. The conversion of lignin and cellulose, hemicellulose rich biomass into ethanol using specific enzymes and/or microbial organisms is collectively referred to as second generation technologies. Technical and economic analyses have shown that the production of ethanol from lignocellulose results in a net gain of energy (Shapouri et al. 2002, Shapouri and McAloon 2004), and that compared to gasoline and ethanol derived from starch/sugar, ethanol produced from lignocellulosic biomass is projected to have the smallest contribution to the emission of CO_2 and the largest net energy production (Farrell et al. 2006). Nevertheless, the production of ethanol from lignocellulosic biomass will need to be considerably more cost effective than is possible with the current technologies before fuel ethanol is economically competitive (Vermerris et al. 2007). Improvements to make this process economically viable are necessary, including efficient and cost effective pretreatment strategies (Ragauskas et al. 2006). Pretreatment is a process during which the stover is subjected to chemical and/or physical agents with the aim of improving the rate and the extent of cellulose and hemicellulose hydrolysis, which is not currently cost effective.

By using different pre-treatment techniques followed by fermentation, the theoretical ethanol yield from sweet sorghum biomass is about 19,400 L ha^{-1}, which is substantially higher than that of switch grass and *Miscanthus* spp (Table 14).

Table 14. Potential ethanol yield from cellulosic biomass of biofuel crops.

Feedstock	Biomass yield ($t\ ha^{-1}$)	Ethanol yield ($L\ t^{-1}$)	Grain yield ($t\ ha^{-1}$)	Total ethanol yield ($L\ ha^{-1}$)
Switch grass	38	450	-	17,100
Miscanthus spp.	25	666	-	16.650
Sweet sorghum	35	500	5	19,400
bmr sorghum	25	600	2	15,760

b) Brown midrib (bmr) mutants

Vascular plants possess a primary cell wall made up of cellulose and hemicellulose with cross linking glucuronoarabinoxylans and a secondary cell wall rich in cellulose (15–30%), hemicellulose (20–40%) and lignin (10–25%) (Sticklen 2008). Spontaneous mutations in any one gene of lignin biosynthetic pathway are associated with prominent brown color of leaf midrib that has reduced lignin content. Reduced lignin content or altered lignin composition will greatly improve ethanol yield as cellulases used in second generation technologies would convert them to sugar due to lower recalcitrance and higher saccharification efficiency. This will also enhance sorghum forage quality by increasing digestibility when fed to cattle. Brown midrib (*bmr*) mutants of sorghum were first developed at Purdue University via chemical mutagenesis (Porter et al. 1978). Since then, additional spontaneous *brown midrib* mutants have been identified, having brown vascular tissue with altered lignin content (Vogler et al. 1994). Both groups of *bmr* mutants, numbered consecutively 1 through 28, show altered cell wall composition, particularly relative to lignin subunit composition, and some have superior forage quality. Allelic relationship of 19 *bmr* lines was established very recently (Saballos et al. 2008). The results point to the fact that there are four independent *bmr* loci, represented by the *bmr*2, *bmr*6, *bmr*12 and *bmr*19 groups, which can also be distinguished by their unique staining pattern with phloroglucinol-HCl. The present day *bmr* mutants are the result of point/deletion mutations at four independent *bmr* loci, represented by the *bmr2, bmr6, bmr12* and *bmr19* groups with unique phloroglycinol-HCl staining characteristics (Figure 6) and changes in G/S subunit lignin composition (Saballos et al. 2008). Current research is focused to introgress *bmr* trait into elite genotypes by repeated cycles of backcrossing and selfing with *bmr* mutant for enhancement of cellulosic ethanol, besides improving forage quality.

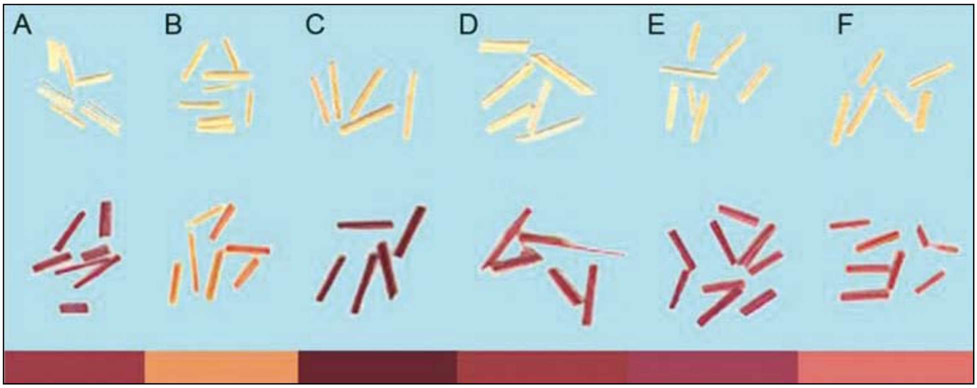

Figure 6. Dissected midribs from the different allelic groups prior to (top) and after staining in acid phloroglucinol. A N2, B bmr2, C bmr6, D N12, E bmr12, F bmr19. The colors at the bottom of the image are included to facilitate the comparison among the stained midribs and represent the predominant color (N2 and N12 are wild types). Source: Saballos et al. 2008.

Recently Xin et al. (2009) isolated 10 new *bmr* mutants in BTx623 TILLING population, *bmr*34 and *bmr*35 were found to be mis-sense mutants of COMT, different from earlier identified alleles in *bmr*12, *bmr*18 and *bmr*26, which contain non-sense mutations resulting in premature stop-codons.

Table 15. Brown midrib sources and improved parental lines.

Source / Lines	
bmr mutant sources	IS 21887 (*bmr*1), IS 21888 (*bmr*3), IS 21889 (*bmr*6), IS 21890 (*bmr*7) and IS 21891 (*bmr*8), IS 40602 (*bmr*12)
Number of high biomass *bmr* B-lines	*bmr*1: (2), *bmr*3: (3), *bmr*7: (6)
Number of high biomass *bmr* R-lines	*bmr*1: (10), *bmr*3: (3), *bmr*7: (9)

Number of lines developed are shown in parenthesis. (Reddy et al. unpublished).

The work on introgression of brown midrib trait using *bmr*1, 3, 7 and 12 mutants into elite hybrid parents (both B and R lines) is in progress at ICRISAT since 2004 (Table 15). Preliminary results indicate that there is considerable reduction in lignin content of hybrid parents vis-a-vis non-*bmr* white midrib lines. The developed *bmr* parental lines (B/R) will be used to develop elite hybrids (high grain and biomass), which are amenable for lignocellulosic ethanol production at lower costs. In 2009, ICRISAT has received *bmr*6 and 12 mutants from USDA-ARS and their iso-genic lines in elite backgrounds.

These new *bmr* mutants will be introgressed to highly adapted biomass lines.

“Atlas *bmr*12’ forage sorghum was developed jointly by the USDA, ARS and the Agricultural Research Division, Institute of Agriculture and Natural Resources, University of Nebraska, and was released in January 2005 for cultivation in USA. Though reduced lignin content in the cell walls favors easy fermentation and digestibility, there is a greater possibility of enhanced susceptibility to biotic stresses, besides lodging (Pederson et al. 2005). Surprisingly, *bmr*6 and *bmr*12 containing genotypes have shown increased resistance to *Fusarium* and *Alternaria* spp. (Funnell and Pedersen 2006). This is probably due to accumulation of phenyl proponoids. It is essential to incorporate lignin-reducing genes into numerous genetic backgrounds and combinations to obtain valuable genotypes in the context of economic viability and sustainability of the farming system.

Biomass yield and biomass conversion efficiency are critical factors for ethanol productivity. Mutations that can potentially improve both the traits would be of immense utility. The newly identified 50 novel mutants will aid in developing new generation energy sorghums (Xin et al. 2009). The cell wall is a major component of biomass and the conversion efficiency is determined by its structure and composition. Plants devote about 2,500 genes to construction and dynamic rearrangement of their cell walls during growth (Yong et al. 2005).

6. Sweet sorghum improvement - Biotechnological approaches

Until early 2000, the lion’s share of funding for biotech research was given for maize, rice, wheat, soybean and cotton. Production of ethanol from cellulosic biomass is a major focus, besides specifically improving the stalk sugar content in sorghum. An initial analysis of the 730-megabase sorghum genome, placing 98% of genes in their chromosomal context using whole-genome shotgun sequence validated by genetic, physical and syntenic information shows that genetic recombination is largely confined to about one-third of the sorghum genome with gene order and density similar to those of rice, and genetic, physical and syntenic information is available for most of the genes (as the genome sequence is available (http://www.phytozome.net/sorghum, Paterson et al. 2009). This will greatly help in comparative mapping with the already available rice genome. The characteristic adaptation of sorghum to drought is attributed to differential miRNA (Sbi-MIR 169), cytochrome p450 and expansins. Use of molecular markers and quantitative trait loci (QTL) will enhance the efficiency and effectiveness of crop improvement. Transgenic approaches also will have a major role to play in the near future.

i) Molecular markers and deployment of QTLs

The highly saturated maps of Menz et al. (2002) and Bowers et al. (2003), and Wu and Huang (2007) have been used to create BAC libraries, isolate genes, correlate genetic and physical maps and provide robust molecular markers for QTL mapping efforts in sorghum. The genome sequence published this year (Paterson 2009) will greatly aid in identifying the SSR and SNP markers and designing their primers.

Table 16. Summary of qualitative and quantitative trait loci identified in sorghum/sweet sorghum.

Trait	Reference
Drought tolerance	Tuinstra et al. (1996, 1997), Crasta et al. (1999), Subudhi et al. (2000), Tao et al. (2000), Xu et al. (2000) and Coulibaly (2002)
Anthracnose	Boora et al. (1998) and Mehta (2002)
Rust	Tao et al. (1998)
Head smut	Oh et al. (1994)
Downy mildew	Gowda et al. (1995) and Oh et al. (1996)
Maturity	Lin et al. (1995) and Childs et al. (1997)
Height	Lin et al. (1995), Pereira and Lee (1995), Murray et al. (2008a)and Murray et al. (2009)
Yield and components	Pereira et al. (1995), Tuinstra et al. (1997), Rami et al. (1998), Sanchez-Gomez (2002), Moran (2003) and Murray et al. (2008a)
Grain quality and mold resistance	Rami et al. (1998), Klein et al. (2001a) and Franks (2003)
Shoot fly	Satish et al. (2009)
Leaf blight resistance	Boora et al. (1999)
Fertility restoration	Klein et al. (2001b)
Pre-harvest sprouting resistance	Lijavetzky et al. (2000)
Greenbug resistance	Katsar et al. (2002)
Midge resistance	Tao et al. (2003)
Tillering	Paterson et al. (1995)
Seed size and dispersal	Paterson et al. (1995)
Sugar content of stalk	Yun-long et al. (2006), Ali et al. (2008), Murray et al. (2008a) and Murray et al. (2009)

A majority of the published research is focused on marker assisted selection (MAS) for biotic and abiotic stresses, besides for yield related traits (Table 16). Ali et al. (2008) has reported clustering of 68 sweet sorghum cultivars into 10 clusters using 41 SSR markers based on polymorphism information content (PIC), which is in agreement with the available pedigree and genetic background information. A number of diverse pairs of sweet sorghum accessions were identified based on simple sequence repeat (SSR) polymorphism and the same can be utilized for hybrid development to enhance sugar content. Yun-long et al. (2006) has constructed a genetic linkage map using 327 markers (40 RFLP, 265 AFLP and 42 SSR) and succeeded in identifying two QTLs, namely qSC-D and qSC-G, that explains 25% phenotypic variance of sugar content. Sugar yield QTL is colocalized with juice yield and stem fresh weight but not with sugar concentration. Therefore, sugar yield per hectare may be best improved by increasing stem fresh weight owing to its high genetic variability and heterosis potential while maintaining maximum sugar concentration and stem juiciness (Murray et al. 2008a). This study further revealed that breeders should be able to improve grain and sugar yields simultaneously, but tradeoffs will increase with stress as developing grain is not a significant sink for whole-plant carbohydrates. It was proved that sbCAD2 is mutated in *bmr*6, *bmr*3 and *bmr*27 (Saballos et al. 2008). The same group has developed molecular markers specific to *bmr*7 and *bmr*25, two novel mutant alleles of the gene encoding caffeic acid o-methyl transferase (COMT). The pace of molecular breeding is bound to increase in the coming years due to recent advances in genomics. There are no reports of MAS for improving stalk sugar and related traits in sweet sorghum genotypes. Nevertheless, the identified QTLs for respective traits can be successfully employed in improvement of sweet sorghum.

Significant QTLs have been found for the traits viz. sucrose percent, dry matter yield, sugar yield, etc, (Natoli et al. 2002, Yun-long et al. 2006). Murray et al. (2008a) have identified the QTLs that influence yield and altered the composition of stem sugar and grain with out pleiotropic effects and suggested that total nonstructural carbohydrate yield could be increased by selecting for major QTLs from both grain and stem sugar. 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). Forage sorghum with *bmr* gene could be developed into novel biomass and bioenergy crop (Sarath et al. 2008) and it has advantage of high biomass due to multicut nature.

ii) Altered gene expression for sucrose accumulation

Efforts to achieve increased yields of sugar over the last three decades, in particular via manipulation of the enzyme ADP (Adenosine di-phosphate) glucose pyrophosphorylase and sucrose isomerase have met with limited success. Other approaches have included manipulation of carbon partitioning within storage organs in favor of starch synthesis, and source–sink relationships. Some of the most promising results so far have come from manipulations that increase the availability of ATP (Adenosine tri-phosphate) for starch synthesis. Future options for achieving increased starch content could include manipulation of starch synthesis (starch synthase) into the cytosol starch degradation in organs in which starch turnover occurs. Stem nodes of transgenic sugarcane plants expressing a bacterial sucrose isomerase accumulates very high level of iso-maltulose; thereby increasing the sugar levels in harvested juice by two fold compared to control plants. This is a significant achievement in the desired direction (Wu and Birch 2007). Sucrose accumulation is poorly understood than starch synthesis. However, recent results from research on sugarcane suggest that total sugar content can be greatly increased by conversion of sucrose into a non-metabolizable isomer. A better understanding of carbohydrate storage and turnover in relation to carbon assimilation and plant growth is required, both for improvement of starch and sugar crops, and for attempts to increase biomass production in second-generation biofuel crops such as sorghum (Smith 2008).

iii) Improvement of biomass quality through lignin modification

Lignocellulosic biomass from a variety of sources, including agricultural residues such as sweet sorghum bagasse, sugarcane bagasse and corn stover, trees and grasses, is a potential source for ‘cellulosic ethanol’ (Lynd et al. 1991; Somerville 2006, 2007). Murray et al. (2008b) reported that many QTLs for structural sugars co-localized with loci for height, flowering time and plant stand while separate genetic controls exist for stem and leaf composition. Therefore, to maximize energy yield from sweet sorghums, component yield traits should be targeted for improvement before compositional traits. However, this methodology utilizing biomass requires a process of efficiently converting cellulose from plant biomass into liquid fuels; it will provide humans with a renewable and carbon-neutral energy source for future sustainable development.

Despite the potential promise of cellulosic ethanol and other cellulose-derived biofuels, several technical obstacles need to be addressed to make the process feasible and economically viable for large-scale adoption. One of the major problems lies in the fact that cellulose in the plant cell wall is crystalline and thus recalcitrant to hydrolysis. This problem is exacerbated by the fact that cellulose is embedded in a complex matrix that includes the phenolic polymer lignin, the presence of which interferes with access of hydrolytic enzymes to the cellulose polymer. Lignin can also adsorb hydrolytic enzymes that are used to generate monosaccharides from lignocellulose, and some lignin degradation products inhibit subsequent fermentation steps (Keating et al. 2006).

To ensure successful biological conversion, the interactions between lignin and the polysaccharide components of the cell wall must be reduced through pre-treatment, a process that is considered to be one of the most costly steps in the whole process (Wyman et al. 2005). Genetic engineering of biofuel feedstock crops with cell-wall structures that are more susceptible to pre-treatment and thus more amenable to hydrolysis, or are sufficiently altered that they require no pre-treatment at all, thereby making biofuels cost-competitive with that of fossil fuels. Different *bmr* mutants can be characterized and can be introgressed into high biomass, staygreen sorghum lines (Vermerris et al. 2007). It is confirmed that *bmr*7*, bmr*12*, bmr*18 and *bmr*25 were found to be mutant alleles of the gene encoding monolignol biosynthetic enzyme caffeic acid-methyl transferase (COMT) (Bout and Vermerris 2003, Saballos et al. 2008), while *bmr*3 and *bmr*6 affects the activity of the enzyme cinnamyl alcohol dehydrogenase (CAD) (Pillonel et al.1991). Recently, a new set of *bmr* mutants (*bmr*28-*bmr*38) were identified in a TILLING population developed from BTx 623 through ethyl methane sulfonate (EMS) mutagenesis (Xin et al. 2009). *bmr*34 and 35 codes for novel alleles of COMT, which have mis-sense mutation unlike *bmr*12, *bmr*18 and *bmr*26 that harbored non-sense mutation resulting in a truncated protein.

Many genetic engineering efforts aimed at improving forage digestibility have focused on down regulation of some of the genes in the well studied lignin biosynthetic pathway (Figure 7). The targets of these experiments and their outcomes are summarized in Table 17. Suppression of genes early in the monolignol biosynthetic pathway, such as PAL, C4H, HCT and C3H, is most effective for reducing lignin content. In contrast, down-regulation of F5H or COMT, which resides on a branch pathway converting guaiacyl (G) to Syringyl (S) greatly reduces the lignin S/G ratio but has little effect on lignin content. In this context, it is noteworthy that, with the exception of CAD down-regulation, the transgenic alfalfa plants listed in Table 16 were generated in the same genetic background and the same promoter was used to drive the corresponding transgenes. Comparison of the digestibility of this isogenic collection of plants revealed a strong negative linear relationship between the forage digestibility and lignin content (Reddy et al. 2005).

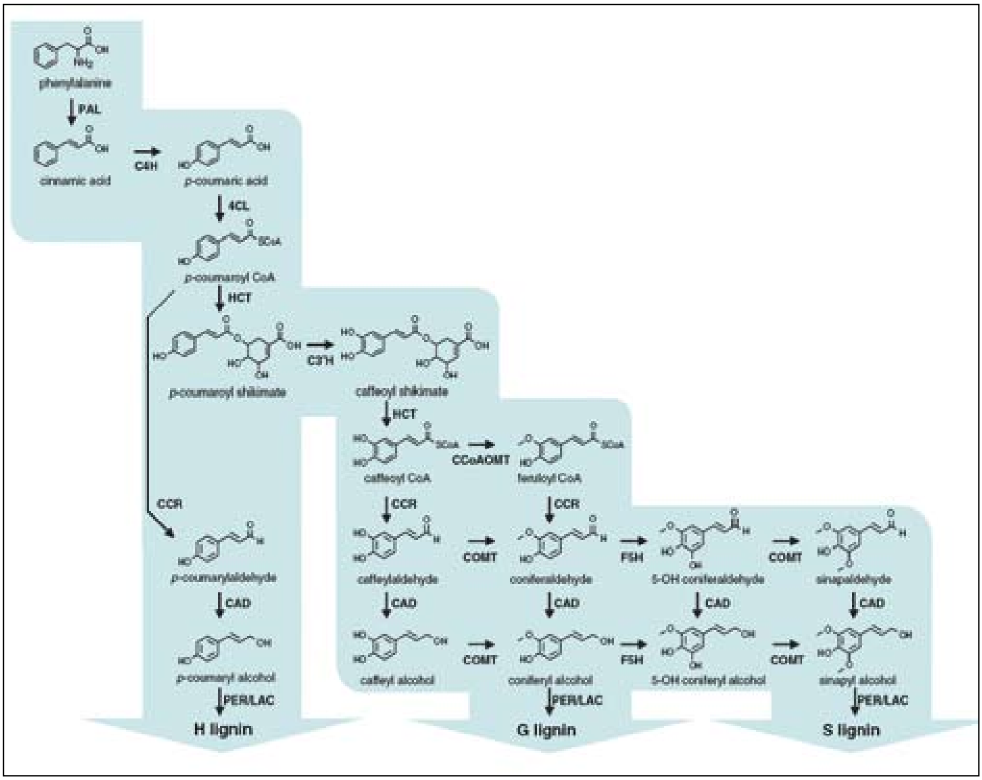

Figure 7. The lignin biosynthetic pathway in flowering plants. The enzymes of the pathway are phenylalanine ammonia lyase (PAL); 4-(hydroxy) cinnamoyl CoA ligase (4CL); cinnamate 4-hydroxylase (C4H); hydroxycinnamoyl CoA shikimate: quinate hydroxycinnamoyl transferase (HCT); p-coumaroylshikimate 3-hydroxylase (C3H); caffeoyl CoA O-methyl transferase (CCoAOMT); (hydroxy) cinnamoyl CoA reductase (CCR); ferulic acid/coniferaldehyde/coniferyl alcohol 5-hydroxylase (F5H); caffeic acid/5-hydroxyferulic acid O-methyltransferase (COMT); (hydroxy) cinnamyl alcohol dehydrogenase (CAD); peroxidase (PER); laccase (LAC).
[Source: Xu Li et al. (2008)].

In stems of transgenic alfalfa lines independently down-regulated in each of six lignin biosynthetic enzymes, recalcitrant to both acid pretreatment and enzymatic digestion is directly proportional to lignin content. Chen et al. (2006) analyzed previously generated alfalfa lines expressing antisense constructs for down-regulating lignin biosynthesis independently at six different steps: Down regulating COMT or CCoAOMT does not affect plant yield, whereas strongly down regulating C3H or HCT reduces biomass (by a maximum of 40%) accompanied, in HCT transgenics, by increased branching. A 166% increase in sugar production would offset a 40% reduction in overall biomass yield. The increased enzymatic hydrolysis of the HCT lines therefore reflects a significant theoretical improvement in fermentable glucose production on a per plant basis in spite of the yield reduction. This is one of the finest examples and expected to have significant implications in the biofuel industry. Many such technologies are expected in the near future, as the research outcomes in these are not being made available in the public domain owing to their vast commercial value.

Table 17. Genetic engineering of lignin biosynthetic genes and its effect on lignin and forage digestibility.

Gene	Species	Lignin content	Digestibility	References
PAL ↓	Tobacco	Reduced	Increased	Sewalt et al. (1997a,b)
C4H ↓	Alfalfa	Reduced	Increased	Reddy et al. (2005)
HCT ↓	Alfalfa	Reduced	Increased	Shadle et al. (2007)
C3'H ↓	Alfalfa	Reduced	Increased	Reddy et al. (2005)
CCoAOMT ↓	Alfalfa	Reduced	Increased	Guo et al. (2001a,b)
F5H ↓	Alfalfa	Unchanged	Unchanged	Reddy et al. (2005)
COMT ↓	Tobacco	Unchanged	Increased	Vailhe et al. (1996)
COMT ↓	Tobacco	Reduced	Increased	Sewalt et al. (1997b)
COMT ↓	Alfalfa	Reduced	Increased	Guo et al. (2001a,b)
COMT ↓	Tobacco	Reduced	Increased	He et al. (2003)
CAD ↓	Maize	Unchanged	Increased	Vailhe et al. (1998)
CAD ↓	Alfalfa	Unchanged	Increased	Baucher et al. (1999)
CAD ↓	Tall fescue	Reduced	Increased	Chen et al. (2003)

Arrows indicate up- or down-regulation of genes.
[Source: adapted from Xu Li (2008)].

The USDOE established the project Genomics: Genome to life (GTL) Program (USDOE 2005). This project is using systems biology, which is based on high-throughput technologies and computational modeling, to aid in our understanding of biological processes related to biofuel production, such as fuel production from lignocellulosic components of biomass. Farrell et al. (2006) pointed out that many important environmental effects of biofuel production are still poorly understood, and that large-scale use of ethanol for fuel will require cellulosic technology. These R&D efforts can open enormous opportunities for the use of wood and other biomass feedstocks for ethanol production. Combined efforts from breeders, molecular biologists, biochemists, microbiologists, physiologists, chemical engineers and ecologists should identify optimal approaches to engineer a smart crop such as sweet sorghum and thereby ensure sustainability in the system.

7. Life Cycle Analysis (LCA) and Clean Development Mechanism (CDM)

i) LCA and complexity

The life-cycle concept is a “cradle to grave” approach linked to products, processes and services in the value chain. In principle, Life-Cycle Assessment (LCA) covers all stages in the life-cycle of a product system, from “earth to earth”. This includes extracting resources, processing them into materials and fuels, producing usable components, manufacturing a product, using and maintaining the product, and its final disposal. LCA quantifies energy and resource inputs and outputs at all stages of a life-cycle, then determines and weighs the associated impacts to set the stage for improvements. The life-cycle approach can be used as a scientific tool for gathering quantitative data to inventory, and weigh and rank the environmental burdens of products, processes and services. Public policy makers, industrialists and private organizations can apply the life-cycle concept to help them make decisions about environmental design and improvement. Unlike more specific “end-of-pipe” approaches to environmental management, decision makers can apply the life-cycle approach to all the upstream and downstream implications of site-specific actions. An example might be changes in emission levels that result from changing a raw material in the production process. Industry use of life-cycle assessment (LCA) as a tool to improve environmental performance is increasing. In LCA, as in any model, a gap exists between accuracy and practicality. As we add details of breadth and depth, we also add complexity, expense and reduced utility. Ultimately, those who undertake LCA projects must make choices about scope and boundaries. Most attempts to develop life-cycle assessments have focused on the first two of four phases, namely, initiation and inventory analysis. A complete LCA study adds two further phases: impact assessment and improvement assessment.

In short, LCA encompasses the assessment in terms of economic cost, energy and environmental cost of all the elements that are involved in the total value chain such as 1. production of raw material 2. biofuel production 3. processing, blending and utilization and 4. environmental impact.

A full life-cycle analysis of the sorghum bioethanol will determine the total amount of greenhouse gas emissions and environmental impact generated throughout the entire development of the fuel (as shown in the schematic model, Figure 8). It examines the costs, energy and environmental impacts from land-preparation, planting, harvesting, transportation, bioethanol conversion, blending and usage of the fuel (cradle to grave or well to tank approach). The methodology and scope of LCA vary both spatially and

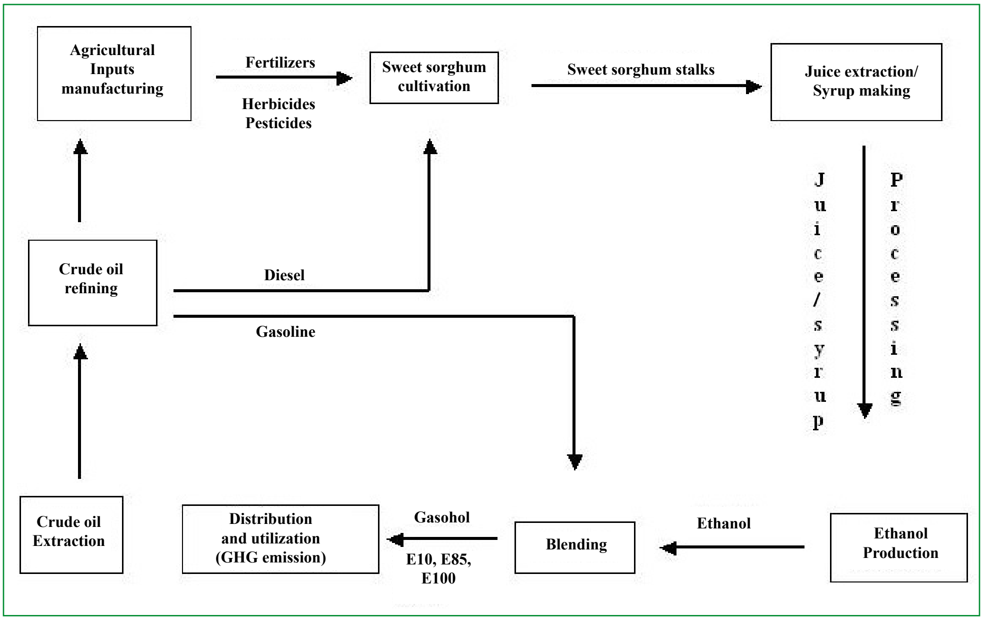

Figure 8. Schematic LCA model for sweet sorghum involving all inputs and outputs.

temporally according to the model used (BEES, UBP06 or Eco-indicator 99). There are very few empirical studies in biofuels and most reports are based on various models (Halleux et al. 2008).

The World Resources Institute (WRI) Policy Note on Energy: Biofuels No. 4 states that even moderate harvest of corn stover and other agricultural residues for use in ethanol production significantly increase soil erosion and greenhouse gases (GHG) emissions. It further adds that alternative best management practices (BMP) for crop production, including zero-tillage, cover cropping, green manuring and precision nitrogen management will efficiently address the negative impacts to air, water and soil resources (Marshall and Sugg 2009). There are no published empirical LCA studies using bioethanol from sweet sorghum. The following are some of the inferences or conclusions at different locations emphasizing the relevance and impact of LCA *vis-a-vis* rising prices of crude oil and GHG emissions.

ii) Results of LCA using biofuels

1. Advances in reformulated gasoline-fueled automobiles, low petroleum prices, and the extensive gasoline infrastructure hamper alternative fuels in competing with gasoline. However, no fuel dominates for all economic, environmental and sustainability attributes. Compressed natural gas

(CNG) is less expensive than gasoline. It has lower pollutant and GHG emissions, and these are large North American reserves. However, onboard storage penalties and the lack of fuel infrastructure lower its attractiveness. Biofuels offer lower GHG emissions, are sustainable, and reduce the demand for imported fuels. Bioethanol would be attractive if the price of gasoline is more than US$78 per barrel or if significant reductions in GHG emissions were required (Maclean et al. 2000).

2. Compared to a reformulated gasoline (RFG) automobile, life cycle GHG emissions are 57% lower for an E85-fueled automobile derived from switch grass and 65% lower for ethanol from corn stover, on a gram of CO_2 equivalent per kilometer basis. Corn stover ethanol exhibits slightly lower life cycle GHG emissions, primarily due to sharing emissions with grain production. Through projected improvements in crop and ethanol yields, results from the mid-term scenario show that GHG emissions could be 25-35% lower than those in 2010 and that, even with anticipated improvements in RFG automobiles, E85 automobiles could still achieve up to 70% lower GHG emissions across the life cycle (Spatari et al. 2005).
3. Life Cycle Assessment was made in two of the major ways of biofuels production in Belgium using specific local data. The environmental impacts assessment revealed that rapeseed methyl ester allows a considerable improvement of the environmental performances compared to fossil diesel, while ethanol from sugar beet offers a more limited benefit compared to petrol (Halleux et al. 2008).
4. An analysis of energy, GHG balances and GHG abatement costs of fuel ethanol produced from cassava was done in Thailand. Positive energy balance of 22.4 MJ/L and net avoided GHG emission of 1.6 kg CO_2 eq./L found for cassava-based ethanol (CE) proved that it would be a good substitute for gasoline, effective in fossil energy saving and GHG reduction. With a GHG abatement cost of US$99 per ton of CO_2, CE is rather less cost effective than the many other climate strategies relevant to Thailand in the short term (Nguyen et al. 2007).
5. Ethanol from corn yields 25% more energy than the energy invested in its production, whereas soybean derived biodiesel yields 93% more. Compared with ethanol, biodiesel releases just 1.0%, 8.3% and 13% of the agricultural nitrogen, phosphorus, and pesticide pollutants, respectively, per net energy gain. Relative to the fossil fuels, bioethanol reduces greenhouse gas emissions by 12% and by 41% if the biodiesel is from soybean. Biodiesel also releases less air pollutants per net energy gain than ethanol. These advantages of biodiesel over ethanol come from lower agricultural inputs and more efficient conversion of feedstocks to

fuel. Until recent increases in petroleum prices, high production costs made biofuels unprofitable without subsidies (Hill et al. 2006).

Studies on LCA at several locations across a variety of biofuel production and usage scenarios point to the fact that transportation biofuels such as synfuel hydrocarbons or cellulosic ethanol, if produced from low-input biomass grown on agriculturally marginal lands or from waste biomass (eg, urban waste, crop residues, etc), could provide much greater supplies and environmental benefits than food-based biofuels. Sweet sorghum nearly matches this requirement, as there are no reports of significant reduction in grain yield at the cost of sugar yield or biomass production.

iii) Limitations of LCA

- Results are highly location/situation specific
- Assumptions in the reference data set
- Significant proportion of secondary data in the analysis
- Huge variation of the results across the models used
- Non-availability of universal/standard model
- Changes in the processing technique/technological upgradation sometimes ignored

The above limitations need to be addressed to have wider acceptance of the LCA results, particularly by the policy makers.

iv) Clean Development Mechanism (CDM)

a) Project methodology/characteristics: The Kyoto Protocol (1997) under the United Nations Framework Convention on Climate Change is designed to curb global GHG emissions and puts emission targets on industrialized countries. These targets can be met by domestic action and by the so called flexible mechanisms, of which one is the Clean Development Mechanism (CDM). Under this mechanism, a project developer may implement clean technology in a developing country and sell the resulting ‘carbon credits’ to a country that can use these to meet their GHG target. Another goal of the CDM is to promote sustainable development in the host country. The CDM Executive Board has approved the biofuel baseline and monitoring methodology, which is a necessary requirement for validation. However, it is expected that the forthcoming UN Climate Conference, 2009, in Copenhagen, Denmark will lead to a global agreement for an affirmative action on further reduction of GHGs worldwide.

Several authors (eg, Sutter 2003) have pointed out the trade-offs between these two goals, ie, carbon credits and sustainable development. The CDM offers an incentive for developing countries to implement climate-friendly projects. Project developers can implement such projects and sell the generated Certified Emission Reductions (CERs) to industrialized countries. In addition to financial benefits, technology cooperation between western and developing countries also happens. For example, western companies may supply the much-needed biofuel-processing equipment. Using the CDM may help lower other barriers such as reluctance to use a new technology, increase the possibility to attract loans, and cooperation from local and national governments.

The CDM project cycle basically comprises two phases: project design and project implementation and can be further subdivided into: i) Project Idea Note: first outline from project developer to potential buyers (not mandatory). ii) Project Design Document (PDD): elaborate description of project, estimated GHG reduction, environmental and social impact, stakeholder comments, and Baseline Methodology and Monitoring Plan. iii) Project validation by a Designated Operational Entity (DOE) and comments on PDD. iv) Registration of project by CDM Executive Board (EB).v) Implementation of the project. vi) Monitoring by the project developer and verification by DOE vii) Issuance of Certified Emission Reductions (CERs) by CDM EB.

b) Project benefits and barriers: Biofuel projects may have clear co-benefits in terms of energy security, energy supply, employment generation, natural resources management and possibly air pollution reduction. Therefore, biofuel CDM projects have the potential to strengthen the sustainable development goal, which is currently under achieved. Future developments in the CDM may increase opportunities for biofuels. These include a possible stronger demand for carbon credits and extension of the scope of eligible activities into sectors and/or programs or policies. Because biofuels have the potential to reduce greenhouse gas emissions, the Kyoto Protocol's CDM offers potential for funding biofuels projects in developing countries. However, owing to political compromises over what should and shouldn't be included in the CDM, this potential is limited by the design of CDM rules and procedures, which largely restricts access by the least developed/developing countries and bypasses smaller producers in those countries. For example:

1) Biomass projects (a common type of CDM project) are generally large in scale and related to grid-based power systems. Their geographical spread is also limited, with most projects in larger developing countries and few in Africa.
2) Rules for land use related projects in the CDM are restricted to include only afforestation, reforestation and certain biomass related processes (such as methane capture from biodegradation) while the European

Union Emissions Trading System (EU ETS), the largest functioning carbon market, does not accept land-use projects.

3) Small farmers are less able to access the carbon market because they lack expertise in implementing complex methodologies, ex-post payment systems mean there is a lack of up front funding for projects and investors are less interested in smaller projects with high risks and long timescales. Small-scale methodologies with simpler requirements and processes for bundling projects have been developed to address some of these issues, but there is currently no small scale methodology for liquid biofuels, and only one large-scale methodology based on use of waste cooking oil for biodiesel (CD4CDM 2007).

c) An illustration: Estimation of CO_2 reduction using biofuel applicable for CDM project: An assumed case study of Beijing, China: Gojash et al. (2007) assumed that bioethanol is produced from sweet sorghum at the plant in the inner Mongol province, near Huhhot City and E10 will be blended at a refinery in Beijing. The project period is assumed to be 10 years starting from 2011 to 2020 and the production capacity 2 million tons per year. The GHG emission from 10% of the total gasoline consumption per year was taken as baseline. The following default data are applied for GHG calculations under the project. Diesel consumption in agricultural operations (62.5 L ha^{-1}), with corresponding emission has a factor of 0.39 kg CO_2e/kg for fertilizer. Soil emissions are estimated at an emission factor of 9.79 CO_2 e/ton sweet sorghum and emissions associated with the transport from field to factory are estimated as 1.86 kg CO_2 e/ton sorghum. As per the report of Shenyang Agricultural University, 5,180 liters of ethanol can be produced from a hectare of sweet sorghum. Industrial emissions while producing bioethanol are zero because the factory uses electricity and steam produced from sorghum bagasse. As a result, the project generates 8.697 million ton CO_2 e between 2011–2020. The difference of emissions between baseline and project is the emission reduction by the project. Therefore, the bioethanol project can reduce GHG emissions by 59.12 million ton CO_2 e in a period of 10 years. By applying carbon price of US$8 per ton CO_2 e, the project gains additional carbon benefits from CER by US$47.3 million per annum and the internal rate of return being 11%, which makes the project economically viable. Negotiations over the next phase of the Kyoto Protocol (post-2012) are considering options for sector wide approaches to the CDM, meaning that developing countries could benefit from finance from developed countries for putting in place biofuels policies. However, perverse incentives could arise, discouraging developing countries from putting in place legislation on biofuels because of rules over ‘additionality’ under the CDM7.

There are alternative carbon markets outside the Kyoto Protocol that show potential for supporting moves towards biofuels production in developing countries. These voluntary markets are smaller, but tend to focus on smaller projects aimed at reducing greenhouse gases and alleviating poverty. However, the quality of projects, in both environmental and social terms, can also be very variable, implying a need for more universal standards.

There are no approved CDM projects based on sorganol so far. It is imperative that IARCs and NARS should take up projects based on bioethanol from sweet sorghum and show the way to sorghum cultivating countries in Africa and Asia to earn tradable CERs.

8. The road ahead

i) Farmers and market perspective

The competitiveness of a biofuels industry is highly dependent on gaining economies of scale. Costly, sophisticated processing plants require massive, steady inflows of feedstock in order to produce sufficient volumes of fuel at competitive prices. A mid-sized bioethanol production facility in India, for example (40 kiloliters per day (KLPD)), costs about US$10 million. It requires about 850 tons of sweet sorghum stalks per day for 105 days in each of two seasons (rainy and postrainy). This in turn requires about 2,400 hectares of sweet sorghum in the rainy season and 4,000 hectares in the postrainy season, engaging about 3,200 small-scale farmers (average 2 ha holding size). The logistics of coordinating thousands of small-scale farmers in a supply chain are formidable. Strategies are needed to vertically-integrate them with large-scale processors in win-win combinations that are economically competitive relative to large-scale farming.

Processors need a reliable stream of quality feedstock at a predictable price and in high volumes; small-scale farmers need a fair sharing of benefits, a predictable price and market, and technical and credit assistance. Research is needed to devise both institutional and technical innovations that make these ends meet. Fortunately, there are examples of successful small-scale farmer to large-scale processor vertical integration in different agricultural sectors that are relevant to the bioenergy situation. The ‘White Revolution’ in India’s dairy industry links millions of small farmers to sophisticated processing, including export markets. Pulpwood, sugarcane and soybeans in India are additional examples. Cotton in Burkina Faso through the organization, Company for the Development of the Textiles (CFDT) is an African example. Another is rural fuel wood markets in Niger and neighboring dryland countries.

These and other successes indicate that:

a. It is possible to integrate vast numbers of small-scale farmers into large-scale commodity production, processing and marketing chains, but this requires research and development paired with skilled management committed to pro-poor development;

b. Public-private partnerships are needed in order to integrate essential policy, entrepreneurial, investment and research elements;

c. These consortia must remain flexible, adaptive, efficient, innovative, and fair to the poor in order to remain competitive over time; the mix of public and private partners helps achieve this;

d. Productivity, quality, economic efficiency, social equity and global competitiveness can be substantially enhanced by such partnerships because they provide both the means (technical and institutional innovations, and capital) and the motivation (increased profits) to stimulate increased investment in agriculture; and

e. Entirely new agro-industries can be jump-started through such partnerships, and old ones revitalized.

Some elements of successful past cases that can be built upon for pro-poor sweet sorghum supply chain development include:

a. Farmer associations and cooperation for integrated, efficient, dependable production and delivery of high-quality feedstock at competitive cost.

b. Backward linkages of processors, input dealers and credit agencies to farmers to provide the latest technical information, bulk inputs at lower prices, institutional credit at lower interest rates, and other production needs.

c. Risk-coping strategies: Rainfed areas are risk-prone, so strategies are essential to avoid crises such as supplemental irrigation, feedstock and farm livelihood diversification, etc.

d. Contract farming: Contractual agreements between individual farmers or farmer groups, and processors help ensure predictable and reliable returns to the farmer while controlling costs for the processor.

e. Capacity-building of farmers and others in the supply chain on production technology; quality issues, value-addition, risk reduction, etc.

f. Research to increase fundamental supply-chain productivity, cost-efficiency and sustainability, resulting in greater economic competitiveness and profitability of the enterprise for all stakeholders.

Connecting sorghum farmers to the commercial distillery industry promises to transform sorghum farming from a low-input, subsistence activity to a modern, technology enhanced commercial enterprise, doubling or tripling grain and stalk yields. Instead of a food-fuel tradeoff, food and feed production will increase substantially. Under good management, sweet sorghum can produce up to 80 tons (fresh weight) of stalks per hectare in just four months of growth. This yields 4,000 liters of 99.6% pure bioethanol, enough for 800 gas tank refills (compact car, 10% blend ratio). Like maize and sugarcane, sorghum is a C_4 crop, highly efficient in converting renewable solar energy into biomass while removing carbon from the atmosphere.

ICRISAT, in partnership with Rusni Distilleries Private Limited, is helping pro-poor entrepreneurs to catalyze sweet sorghum industries in India, Kenya, Indonesia, Mexico, Nigeria, Mozambique, the Philippines and Uganda. Tata Chemicals Limited (TCL) has already commissioned a 30 KLPD sweet sorghum based distillery at Nanded, Maharashtra, India. Scientists from the International Livestock Research Institute (ILRI) have found that the residual stalk material ("bagasse") can be pressed into nutritious feed blocks for cattle and sheep. Dryland farmers depend heavily on livestock. It is apparent that developing successful pro-poor biofuel supply chains requires sophisticated institutional innovation, constant experimentation and fine-tuning. Learning from comparative analyses of pioneering attempts, and sharing success principles with potential pro-poor investors, policy-makers and other key stakeholders, are priorities for **BioPower**.

The success and spread of sweet sorghum depends on:

- The establishment of seed systems to produce sufficient basic/certified seed materials in each country, and market linkages between farmer and industry/enterprises are essential to achieve the targeted benefits.
- Develop strategies for fast-track evaluation (biophysical and socioeconomic) of the available sweet sorghum cultivars to facilitate business incubation and utilization in the biofuel industry and seed systems to provide ready availability of quality seeds.
- Understand the available market opportunities, energy policies and environmental implications for expansion of the biofuel industry by developing business models and establishing strategic partnerships with the biofuel industry, and linking small farmers to markets.
- Genetic enhancement of sweet sorghum varieties and hybrid parents including the brown midrib types for high biomass, juice and sugar yields, improved sugar quality and resistance/tolerance to the most important abiotic and biotic stresses.

- Develop and optimize sweet sorghum crop management, large scale on farm testing of new cultivars and IPM practices for higher productivity and quality of sweet sorghum feedstock.

Knowledge sharing, and project management and monitoring.

Vertical and horizontal integration of farmer–markets–industrialist is essential for solving the issues to replicate the success story of Brazil in energy security in other SAT countries.

ii) Productivity enhancement

The productivity of sweet sorghum needs to be enhanced by following these two approaches.

a) Genetic enhancement

There is plenty of genetic variation for all the component traits of sugar yield such as %Brix, stalk weight, plant height, juice weight and juice volume. Other traits such as stalk girth, days to 50% flowering, stalk harvest index, fermentation efficiency and stalk-stover ratio do express considerable variability apart from grain yield traits. The heritability for plant height, flowering time, test weight and bagasse was high, while stem juiciness, sugar concentration in stems, total sugar, juice fructose, juice glucose and sugar yield were low. Almost all these traits have positive correlation and regression with sugar yield, even though with considerable differences observed in rainy and postrainy seasons. Most of the qualitative traits have high additive gene action while calculated metric traits (eg, sugar yield, grain yield) showed non-additive dominance and epistasis as explained in the previous sections (5, iv to vii). Therefore, breeders and molecular biologists are urged to use a wise mix of conventional breeding methods along with MABC and EcoTILLING to exploit natural genetic variation. Reverse genetic approaches such as microarray and TILLING will aid in identification and cloning of candidate genes for a specific trait dissection and improvement.

b) Agronomic best-bet practices

The already standardized agronomic practices for grain sorghum will not be applicable to sweet sorghum in entirety as sweet sorghums put forth 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 G×GE interaction of sugar yield, its competent traits as described earlier [under section 5(vii)]. Standardization of optimized spacing (45×15 cm/ 60×15 cm/ 75×15 cm), fertilizer application, intercultural operations (thinning, weeding, soil mulch), irrigation schedule (both Alfisols and Vertisols apart from seasons), harvesting timing and methodology will greatly enhance the productivity of sweet sorghum. The present day multi-feedstock distilleries can successfully run on a variety of feedstocks. Therefore, studies on intercropping or relay cropping with cassava, sugarcane, sugar beet, soybean, jatropha, pongamia, etc, are required to enhance period of raw material availability. Agronomic and physiological measures aiding in increasing the period of industrial utilization (PIU) of sweet sorghum (eg, customized fertilizer application, irrigation at physiological maturity, spraying GA, ethrel, solubar, etc, or soil application of micronutrients or other amendments to delay maturity, etc) will further strengthen 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.

iii) Potential of lignocellulosic biomass for ethanol production

A significant advantage of developing and using dedicated crops and trees for biofuels is that the plants can be bred for such purpose. This could involve development of higher carbon to nitrogen ratios, higher yields of biomass or oil, cell wall lignocellulose characteristics that make the feedstock more amenable for processing, reduced environmental impacts and traits enabling the plant species to be cultivated on marginal land or abandoned land no longer suitable for quality food production. Several technologies are available to improve these traits, including traditional plant breeding, genomic approaches to screening natural variation and the use of genetic modification to produce transgenic plants. Research may also open up new sources of feedstocks from, for example, novel non-food oil crops, the use of organisms taken from the marine environment such as algae, or the direct production of hydrocarbons from plants or microbial systems.

a) Improving biomass productivity

There is a vast scope associated with challenges in improving the per day biomass productivity of different biofuel feedstocks to realize the potential benefits of second generation ethanol production. The potential of ethanol yields using second generation technology for some of the feedstocks are given in Table 18.

Table 18. The potential of ethanol yields for some of the feedstocks.

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

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

In case of sweet sorghum, the major component traits for biomass are plant height, stalk weight, stalk girth, internodal length, number of tillers, ratoonability, leaf area, number of leaves. Other qualitative traits such as photo and thermo sensitivity, cellulose & hemi-cellulose content, etc, can also be exploited. A judicious mix of conventional breeding and novel molecular tools such as MABC (for known QTLS), TILLING for mutants identification (Xin et al. 2009) and EcoTILLING (Comai et al. 2004) to identify natural genetic variants, haplotyping using SNPs (Bhattramakki and Rafalski 2001) involving system biological approach will go a long way in realizing high biomass energy sorghums.

b) Improving biomass quality through altering composition

The hemi-cellulose and cellulose are enclosed by lignin (which contains no sugars), making sorghum stover difficult to convert into ethanol, thereby increasing the energy requirement for processing. The brown midrib (*bmr*) mutant sorghum lines have significantly lower levels of lignin content (51% less in stems and 25% less in leaves) (Porter et al. 1978). Research at Purdue University, USA showed 50% higher yield of the fermentable sugars from stover of certain sorghum *bmr* lines after enzymatic hydrolysis [www.ct.ornl.gov/symposium/index_files/ (6Babstracts /6B_01.htm)]. Therefore, the use of *bmr* sorghum cultivars would reduce the cost of biomass-based ethanol production by way of removing pre-processing in the production cycle.

Sweet sorghum cultivation on just 20% of India's sorghum area would meet the nation's need for bioethanol at its current 10% blending in petrol (1.5 billion liters per annum), without expanding into non-agricultural lands. Leaf stripping and crushing operations to extract sugar-rich juice from the stalks provide employment. A medium-sized processing facility can produce 40,000 liters of bioethanol per day, providing benefits to 5,000 farmers and 4,000 other workers. One billion dollars of India's oil-importation money could be re-invested in the rural drylands annually. Similar success can be replicated in sub-Saharan African countries given their vast semi-arid and arid tracts. The potential yield of ethanol for different crops is given in Table 19. Second generation lignocellulosic technologies will play a greater role in meeting the energy requirements of resource poor African countries in future.

Table 19. Potential ethanol yields by feedstock in sub-Saharan Africa.

Feedstock	Biomass yield (tons year^{-1})	Ethanol yield (liters ton^{-1})	Ethanol yield (L ha^{-1} 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

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}.

Source: www.olade.org.ec/biocombustibles/documents/pdf-17.pdf;

9. Conclusions

ICRISAT has launched a global **BioPower** Initiative to empower the dryland poor farmers to benefit from, rather than be marginalized by the bioenergy revolution. **BioPower** looks at biofuel needs through the eyes of the poor, in terms of risks managed, synergies sought, and choices made amidst a wide range of livelihood needs, opportunities, capacities and constraints. The **BioPower** strategy focuses on feedstock sources and approaches that do not compete with food production but rather produce food as well as fuel, and may enhance food production by stimulating increased input use and crop management intensity. This initiative can be strengthened by establishing a bioethanol/sorganol based distillery in some of the developing countries in Africa, Asia and Latin America.

Sorghum is relatively inexpensive to grow with high yield potential, and can be used to produce a range of high value-added products such as ethanol, energy and distillers dried grains. This crop consumes half the quantity of water required by sugar beet and a third of the requirement for sugarcane or corn. Its short duration, ability to produce large quantities of dry matter, low water requirement, and availability of hybrid seed technology makes it amenable for growing in different seasons to schedule feedstock supply on a regular basis. This has led to the establishment of distilleries for commercial exploitation of sweet sorghum-based bioethanol (Sorganol) in India, USA, Mexico, the Philippines, Nigeria, Mozambique and other countries.

A limiting factor for its widespread cultivation is the limited availability of varieties/hybrids adapted to different agro-climatic conditions resisting both biotic and abiotic stresses, including colder climate. Consequently, research should address the optimization of sweet sorghum as an energy crop through breeding for enhanced productivity under limited resources available with SAT farmers. Genetic improvement should focus on stalk sugar, biomass quantity and quality and general agronomic traits (such as water and nutrient use efficiency) and, in particular, adaptation of sweet sorghum to colder, arid saline, and alkaline conditions. Also, the traits that aid in sequential plantings to widen the harvest window need to be improved. If a new cultivar is to be introduced or to be grown in large command area of the biorefinery or sugar industry, initial experiment must be planted on a pilot scale and both stalk and ethanol yields should be estimated before the commercial plantation by the industry.

There is a need to develop and evaluate cultivars producing high stalk yield per unit time, input, energy and land area in different agro-climatic areas of the country. Other research areas on quality and processing which needs immediate attention include high ethanol yield, fermentation efficiency, diffusion, diversified products from bagasse (power, pulp, bio-manure, cattle feed, etc).

The project should also address agronomic practices and harvesting technologies leading to improved yield, quality, sustainability and competitiveness of sweet sorghum production. Environmental and economic analysis of sweet sorghum cultivation, including energy balance and life cycle assessment are essential. Success in crop improvement depends on using the genetic diversity conserved in germplasm collections. A new paradigm is emerging with the integration of biotechnology and the cutting edge genomic sciences for the conservation and use of genetic resources. These resources are strategic factors for the development of nations, such as Brazil, that have agribusiness as a strong and competitive area of development.

Brazil’s success story (PROALCOOL) in production and export of bioethanol from sugarcane could serve as a model for developing countries in the SAT region as it encompasses at least three driving forces: (i) economic – the influence of oil prices (ii) social – the need to generate jobs and new opportunities for poor farmers; and (iii) environmental – to produce a sustainable, renewable, and eco-friendly fuel.

Advanced research laboratories working on biofuels need to come together for implementation of CDM projects on biofuels and evolve guidelines for standardized LCA, which is somewhat similar to Minimum Information about microarray experiment (MIAME). Relevant data on LCA should be made freely accessible. This will help in popularization of the biofuel industry in developing countries and help researchers to address the problematic issues.

The Declaration of the high-level conference on world food security on 5 June 2008 in Rome states, “We are convinced that in-depth studies are necessary to ensure that production and use of biofuels is sustainable in accordance with the three pillars of sustainable development and takes into account the need to achieve and maintain global food security. We are further convinced of the desirability of exchanging experiences on biofuels technologies, norms and regulations. We call upon relevant intergovernmental organizations, including FAO, within their mandates and areas of expertise, with the involvement of national governments, partnerships, the private sector, and civil society, to foster a coherent, effective and results-oriented international dialogue on biofuels in the context of food security and sustainable development needs”. This declaration reiterates that energy security through renewable sources is essential without undermining food security.

The IPEEC declaration noted that energy efficiency is one of the quickest, greenest, and most cost-effective ways to address energy security and climate change while ensuring economic growth, a conclusion supported by a recent study from the American Council for an Energy Efficient Economy (ACEEE). The report, released in June 2008 notes that a 20% efficiency gain in the US economy by 2030 could provide an estimated 800,000 net jobs while contributing to a slight increase in the nation’s gross domestic product. ACEEE notes that most national energy modeling efforts fail to account for energy efficiency’s contribution.

The biofuels initiative in the United States is accelerating research to make cellulosic ethanol (second generation biofuel) cost competitive by 2012. Several laboratories are engineering new microorganisms to improve pathways related to lignocellulose hydrolysis and subsequent fermentation into fuel.

Bioethanol from sweet sorghum (sorganol) is potentially a win-win solution. Sorganol will not be the unique solution, but will compliment other renewable sources of energy and contribute to address some of the problems – eg, reduction of GHG emissions, improving air quality in large cities, reducing dependency on imported oil, creating jobs in rural areas and improving quality of life in developing countries. As the demand for biofuels rapidly expands, its associated production systems and supply chains are consolidating. Forward-thinking management systems could significantly enhance ecological sustainability and livelihood development, particularly for poor farmers in the developing world. International trade will be crucial to enlarge the share of bioethanol in future transport energy demand. All the nations irrespective of the development index, should join hands in formulation of policies that target the entire innovation chain to ensure that the development and use of biofuels in general and sorganol in particular, follow an integrated pathway, which simultaneously targets climate change mitigation and adaptation, energy security and all round sustainable economic development.

10. References

AICSIP (All India Coordinated Sorghum Improvement Project). 2004. Sorghum physiology. All India Coordinated Sorghum Improvement Project Annual Progress Report for 2003–2004. AICSIP Pub. No. 7/Phy/2004, Pp. 50. National Research Centre for Sorghum (NRCS), Rajendranagar, Hyderabad, AP, India

AICSIP (All India Coordinated Sorghum Improvement Project). 2005. Physiology and sweet sorghum. All India Coordinated Sorghum Improvement Project Annual Progress Report for 2004–2005. AICSIP Pub. No. 8/Physiology and Sweet Sorghum/2005, Pp. 80. National Research Centre for Sorghum (NRCS), Rajendranagar, Hyderabad, AP, India.

AICSIP (All India Coordinated Sorghum Improvement Project). 2006. All India Coordinated Sorghum Improvement Project Annual Progress Report for 2005–2006. AICSIP Tech. Pub. No– 3/Sweet Sorghum and Physiology/2006 (Book 3 of 3-agm06), Pp. 100. National Research Centre for Sorghum (NRCS), Rajendranagar, Hyderabad, AP, India

AICSIP (All India Coordinated Sorghum Improvement Project). 2007. Sweet sorghum and physiology. All India Coordinated Sorghum Improvement Project Annual Progress Report for 2006–2007. AICSIP Tech. Pub. No. 3/Sweet Sorghum and Physiology/2007 (Book 3 of 3-agm07 pre-meet), Pp. 102. National Research Centre for Sorghum, Rajendranagar, Hyderabad, A.P., India.

AICSIP (All India Coordinated Sorghum Improvement Project). 2008. Sweet sorghum physiology. All India Coordinated Sorghum Improvement Project Annual Progress Report for 2007–2008. AICSIP Tech. pPb. No. 3/Sweet Sorghum and Physiology/2008 (Book 3 of 3-agm07 pre-meet), Pp. 100. National Research Centre for Sorghum, Rajendranagar, Hyderabad, AP, India

Ali ML, Rajewski JF, Baenziger PS, Gill KS, Eskridge KM and **Dweikat I.** 2008. Assessment of genetic diversity and relationship among a collection of US sweet sorghum germplasm by SSR markers. Mol. Breeding 21:497–509.

Almodares A, Sepahi A and **Shirvani M.** 1997. Sweet sorghum cultural practices in Iran. Pages 175–183 *in* Proceedings of the First International Sweet Sorghum Conference, 14–19 September 1997, Beijing, China (Li Dajue, ed.). Beijing, China: Institute of Botany, Chinese Academy of Sciences.

Almodares A, Taheri R and **Adeli S.** 2008. Evaluation of some sorghum [*Sorghum bicolor* (L.) Moench] cultivars and lines as sweet, dual purpose, and grain types. Journal of Tropical Agriculture 46(1–2):62–63.

Anonymous. 2008. Sweet sorghum physiology. Directorate of Sorghum Research Annual Report (in press).

Argonne National Laboratory model-GREET1.7. 2007. http://www.transportation. anl. gov/pdfs /TA/419.pdf

Badger PC. 2002. Ethanol from Cellulose: A general review. Pages 17−20 *in* Trends in New Crops and New Uses (Janick J, ed.). Alexandria, VA, USA: ASHS Press.

Bailey BK. 1996. Performance of ethanol as a transportation fuel. Pages 37−60 in Hand book on bioethanol: Production and utilization. Applied Energy Technology Series (Wyman CE, ed.). Taylor and Francis. .

Bapat DR, Jadhav HD, Gaur SL and **Salunke CB**, 1986. Screening of sweet sorghum cultivars for production of quality syrup and jaggery. Current Research Report, Mahatma Phule Agricultural University, 2:65–71.

Baucher M, Bernard-Vailhe MA, Chabbert B, Besle JM, Opsomer C, Van Montagu M and **Botterman J.** 1999. Down-regulation of cinnamyl alcohol dehydrogenase in transgenic alfalfa (*Medicago sativa* L.) and the effect on lignin composition and digestibility. Plant Mol Biol 39:437–447.

Berg C. 2004. World fuel ethanol analysis and outlook. Available at http://www.distill. com/World-Fuel-Ethanol-A&O-2004.html.

Bhattramakki D and **Rafalski A.** 2001. Discovery and application of single nucleotide polymorphism markers in plants. *Plant Genotyping: The DNA Fingerprinting of Plants (Henry RJ, ed.).* Wallingford Oxon, UK: CABI Publishing.

Blümmel M, Rao SS, Palaniswami S, Shah L and **Reddy BVS.** 2009. Evaluation of sweet sorghum [*Sorghum bicolor* (L.) Moench] used for bio-ethanol production in the context of optimizing whole plant utilization. Animal Nutrition and Feed Technology. 9:1–10.

Boora KS, Frederiksen RA and **Magill CW.** 1998. DNA-based markers or a recessive gene conferring anthracnose resistance in sorghum. Crop Science 38:1708–1709.

Boora KS, Frederiksen RA and **Magill CW.** 1999. A molecular marker that segregates with sorghum leaf blight resistance in one cross is maternally inherited in another. Mol. Genet. Gen. 261:317–322.

Bout S and **Vermerris W.** 2003. A candidate gene approach to clone the sorghum Brown midrib gene encoding caffeic acid O-methyl-tranferase. Mol. Gent. Gen. 269:205–214.

Bowers JE, Abbey C, Anderson S, Chang C, Draye X, Hoppe AH, Jessup R, Lemke C, Lennington J, Li Z, Lin Y, Liu S, Luo L, Marler BS, Ming R, Mitchell SE, Qiang D, Reischmann K, Schulze SR, Skinner DN, Wang Y, Kresovich S, Schertz KF and **Paterson AH.** 2003. A high-density genetic recombination map of sequence-tagged sites for sorghum, as a framework for comparative structural and evolutionary genomics of tropical grains and grasses. Genetics 165:367–386.

Brown PJ, Klein P, Bortiri E, Acharya C, Rooney W and **Kresovich S.** 2006. Inheritance of inflorescence architecture in sorghum. Theor. Appl. Genet. 113:931–942.

Channappagoudar BB, Biradar NR, Patil JB and **Hiremath SM.** 2007. Assessment of sweet sorghum genotypes for cane yield, juice characters and sugar levels. Karnataka Journal of Agricultural Sciences 20(2):294–296.

Chapman K. 2002. Back-to office report, Food and Agricultural Organization of United Nations (FAO), FAO/RAP.

Chen F, Reddy MSS, Temple S, Jackson L, Shadle G and **Dixon RA.** 2006. Multi-site genetic modulation of monolignol biosynthesis suggests new routes for formation of syringyl lignin and wallbound ferulic acid in alfalfa (*Medicago sativa* L.). Plant J. 48:113–124.

Childs KL, Miller FR, Cordonnier-Pratt MM, Pratt LH, Morgan PW and **Mullet JE.** 1997. The sorghum photoperiod sensitivity gene Ma3 encodes a phytochrome B1. Plant Physiol. 113:611–619.

Comai L, Young K and **Till BJ.** 2004. Efficient discovery of DNA polymorphisms in natural populations by EcoTILLING. Plant J. 37:778–786.

Coulibaly S. 2002. Marker-assisted selection for staygreen in *Sorghum bicolor* L. Moench. PhD dissertation. Texas Tech University, Lubbock, TX.

Crasta OR, Xu WW, Rosenow DT, Mullet JE and **Nguyen HT.** 1999. Mapping of postflowering drought resistance traits in grain sorghum: association between QTLs influencing premature senescence and maturity. Mol. Gen. Genet. 262:579–588.

de Gorter H and **Just DR.** 2008. Water' in the U.S. ethanol tax credit and mandate: Implications for rectangular deadweight costs and the corn-oil price relationship. Paper for presentation at the ASSA annual meetings in New Orleans, 4–6 January 2008.

Dufey A. 2006. Biofuels production, trade and sustainable development: emerging issues. London: International Institute for Environment and Development (IIED).

Eberhart SA and **Russell WA.** 1966. Stability parameters for comparing varieties. Crop Sci. 6:36–40.

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

FAO. 2008. High-level conference on world food security: The challenges of climate change and bioenergy. Rome, 3–5 June 2008. Rome, Italy: FAO.

Fargione J, Hill J, Tilman D, Polasky S and **Hawthorne P.** 2008. Land clearing and the biofuel carbon debt. Science Online, 7 February 2008.

Farrell AE, Plevin RJ, Turner BT, Jones AD, O'Hare M and **Kammen DM.** 2006. Ethanol can contribute to energy and environmental goals. Science 311 (5760):506–508.

Ferraris R. 1981. Early assessment of sweet sorghum as an agro industrial crop 1. Varietal evaluation. Australian Journal of Agriculture and Animal Husbandry, 21:75–82.

Franks CD. 2003. The efficacy of marker-assisted selection for grain mold resistance in sorghum. PhD Dissertation. Texas A&M University, College Station, Tx., USA.

Funnel DL and **Pederson JF.** 2006. Reaction of sorghum lines genetically modified for reduced lignin content to infection by *Fusarium* and *Alternaria* spp. Plant Disease 2006:331–338.

Ganesh S, Fazlullah Khan AK and **Senthil N.** 1996. Heterosis studies for grain yield characters in sweet sorghum. Madras Agric. J. 83(10):655–658.

Ganesh S, Fazlullah Khan AK, Suresh M and **Senthil N.** 1995. Character association for alcohol yield in Sweet Sorghum. Madras Agric. J 82(5):361–363.

Gojash O, Fukuda A and **Fukuda T.** 2007. Estimation of CO_2 emissions reduction using alternative energy–Potential application of Clean Developed Mechanism (CDM) in the Transport sector to developing countries. IATSS Research 31(1):32–40.

Goldemberg J. 2007. Ethanol for a sustainable energy future. Science 315:808–810.

Gowda PS, Xu GW, Frederiksen RA and **Magill CW.** 1995. DNA markers for downy mildew resistance genes in sorghum. Genome 38:823–826.

Guo D, Chen F, Inoue K, Blount JW and **Dixon RA.** 2001a. Downregulation of caffeic acid 3-*O*methyltransferase and caffeoyl CoA 3-*O*-methyltransferase in transgenic alfalfa: Impacts on lignin structure and implications of the biosyntrhesis of G and S lignin. The Plant Cell 13:73−88.

Guo D, Chen J, Wheeler J, Winder J, Selman A, Peterson M and **Dixon. RA.** 2001b. Improvement of in rumen digestibility of alfalfa forage by genetic manipulation of lignin *O*-methyltransferases. TransgenicResearch 10:457−464.

Hallam A, Anderson IC and **Buxton DR.** 2001. Comparative economic analysis of perennial, annual, and intercrops for biomass production. Biomass and Bioenergy 21:407–424.

Halleux H, Lassaux S, Renzoni R and **Germain A.** 2008. Comparative life cycle assessment of two biofuels ethanol from sugar beet and rapeseed methyl ester. Int J LCA 13 (3):184–190.

Hill J, Nelson E, Tilman D, Polasky S and **Tiffany D.** 2006. Environmental, economic and energetic costs and benefits of biodiesel and ethanol fuels. Proceedings of the National Academy of Sciences (PNAS); 103:11206–11210.

IEA. 2006. The energy situation in Brazil: An overview. Available at http://www.iea.org/textbase/papers/2006/brazil. Paris, France: International Energy Agency.

Katsar CS, Paterson AH, Teetes GL and **Peterson GC.** 2002. Molecular analysis of sorghum resistance to the greenbug (Homoptera: Aphididae). J. Econ. Entomol. 95:448–457.

Keating JD, Panganiban C and **Mansfield SD**. 2006. Tolerance and adaptation of ethanologenic yeasts to lignocellulosic inhibitory compounds. Biotech. and Bio Engg. 93:1196−1206.

Klein RR, Klein PE, Chhabra AK, Dong J, Pammi S, Childs KL, Mullet JE, Rooney WL and **Schertz KF.** 2001b. Molecular mapping of te rf1 gene for pollen fertility restoration in sorghum (*Sorghum bicolor* L.). Theor. Appl. Genet. 102:1206–1212.

Klein RR, Rodriguez-Herrera R, Scheulter JA, Klein PE, Yu ZH and **Rooney WL.** 2001a. Identification of genomic regions that affect grain mold incidence and other traits of agronomic importance in sorghum. Theor. Appl. Genet. 102:307–319.

Licht FO. 2006. World Ethanol and Biofuels Report, Page 365 *in* Vol. 4, No. 16 and page 391 *in* Vol. 4, No. 17. UK: Tunbridge Wells.

Lijavetzky D, Martinez MC, Carrari F and **Hopp HE.** 2000. QTL analysis and mapping of pre-harvest sprouting resistance in sorghum. Euphytica 112:125–135.

Lin YR, Schertz KF and **Paterson AH.** 1995. Comparative analysis of QTL affecting plant height and maturity across the Poaceae in reference to an interspecific sorghum population. Genetics 144:391–411.

Lobell DB and **Field CB.** 2007. Global scale climate-crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2 014002.

Lynd LR, Cushman JH, Nichols RJ and **Wyman CE. 1991.** Fuel ethanol from cellulosic biomass. 251:1318–1323.

MacLean HL, Lave LB and **Lankey R.** 2000. A life-cycle comparison of alternative automobile fuels. Journal of the Air and Waste Management Association 50:1769–1779.

Mallikarjun H, Khanure SK and **Kachapur MD**. 1998. Correlation and path analysis for juice quality parameters in sweet sorghum genotypes. Madras-Agricultural-Journal. 85(3/4):207–208.

Marshall L and **Sugg Z.** 2009. Corn stover for ethanol production: Potential and pitfalls. WRI Policy Note 4. Energy: Biofuels. www.wrio.org/policynotes.

Mehta PJ. 2002. Anthracnose resistance genes in sorghum: characterization and molecular markers. PhD Dissertation. Texas A&M University, College Station, Tx., USA.

Menz MA, Klein RR, Mullet JE, Obert JA, Unruh NC and **Klein PE.** 2002. A high density genetic map of *Sorghum bicolor* L. Moench based on 2926 AFLP, RFLP, and SSR markers. Plant Mol. Biol. 48:483–499.

Meshram MP, Atale SB, Murumkar RD and **Raut PB**. 2005. Heterosis and heterobeltiosis studies in sweet sorghum. Ann. Plant Physiol.19:96−98.

Monk RL, Miller RS and **McBec GG.** 1984. Sorghum improvement for energy production. Biomass 6:145–153.

Monti A, Di Virgilio N and **Venturi G.** 2007. Mineral composition and ash content of six major energy crops. Biomass and Bioenergy 32:216–223.

Moran JL. 2003. Quantitative trait loci affecting the agronomic performance of a *Sorghum bicolor* L. Moench recombinant inbred restorer line population. PhD dissertation. Texas A&M University, College Station, Tx., USA.

Murray SC, Rooney WL, Hamblin MT, Mitchell SE and **Kresovich S**. 2009. Sweet sorghum genetic diversity and association mapping for Brix and height. The Plant Genome 2:48−62.

Murray SC, Rooney WL, Mitchell Se, Sharma A, Klein PE, Mullet JE and **Kresovich S**. 2008a. Genetic improvement of sorghum as a biofuel feedstock: II. QTL for stem and leaf structural carbohydrates. Crop Sci. 48:2180−2193.

Murray SC, Sharma A, Rooney WL, Klein PE, Mullet JE, Mitchell SE and **Kresovich S**. 2008b. Genetic improvement of sorghum as a biofuel feedstock: I. QTL for stem sugar and grain nonstructural carbohydrates. Crop Sci. 48:2165−2179.

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K and **Grübler A.** 2000. Special report on emissions scenarios, Working Group III, Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge, UK, Pp. 595. (ISBN 0 521 80493 0) (http://www.grida.no/climate/ipcc/emission/index.htm).

NARI (Nimbkar Agricultural Research Institute). www.nariphaltan.org/

Nass LL, Pereira PAA and **David Ellis.** 2007. Biofuels in Brazil: An Overview. Crop Sci. 47:2228–2237.

NASS. 2007. Acreage June 2007.Agricultural statistics board, USDA, NASS.

Natoli A, Gorni C, Chegdani F, Ajmone Marson P, Colombi C, Lorenzoni C and **Marocco A.** 2002. Identification of QTLs associated with sweet sorghum quality. Maydica 47:311–322.

Nguyen TLT, Gheewala SH and **Garivait S.** 2007. Energy balance and GHG-abatement cost of cassava utilization for fuel ethanol in Thailand. Energy Policy 35:4585–4596.

OECD Council at Ministerial Level Meeting. 2007. Innovation: Advancing the OECD Agenda for Growth and Equity, Paris, 15–16 May 2007.

Oh BJ, Frederiksen RA and **Magill CW.** 1994. Identification of molecular markers linked to head smut resistance gene (SHS) in sorghum by RFLP and RAPD analysis. Phytopathology 84:830–833.

Oh BJ, Frederiksen RA and **Magill CW.** 1996. Identification of RFLP markers linked to a gene for downy mildew resistance in sorghum. Can. J. Bot. 74:315–317.

Paterson AH, Lin YR, Li Z, Schertz KF, Doebley JF, Pinson SRM, Liu, Stansel JW and **Irvine JE**. 1995. Convergent domestication of cereal crops by independent mutations at corresponding genetic loci. Science, 269:1714–1717.

Paterson AH, Bowers JE, Bruggmann R, Dubchak I, Grimwood J, Gundlach H, Haberer G, Hellsten U, Mitros T, Poliakov A, Schmutz J, Spannagl M, Tang , Wang X, Wicker T, Bharti AK, Chapman J, Feltus FA, Gowik U, Grigoriev IV, Lyons E, Maher CA, Martis M, Narechania A, Otillar RP, Penning BW, Salamov AA, Wang Y, Zhang L, Carpita NC, Freeling M, Gingle AR, Hash CT, Keller B, Klein P, Kresovich S, McCann MC, Ming R, Peterson DG, Mehboob-ur-Rahman, Ware D, Westhoff P, Mayer KFX, Messing J and **Rokhsar DS.** 2009. The *Sorghum bicolor* genome and the diversification of grasses. Nature 457:551–556.

Patil DV, Makne VG and **Patil RA.** 1995. Character association and path coefficient analysis in sweet sorghum (*Sorghum bicolor* (L.) Moench). PKV-Research-Journal 19(1):21–24.

Pedersen JF, Vogel KP and **Dunnell DL.** 2005. Impact of reduced lignin on plant fitness. Crop Sci. 45:812–819.

Pereira MG and **Lee M.** 1995. Identification of genome regions affecting plant height in sorghum and maize. Theor. Appl. Genet. 90:380–388.

Pereira MG, Ahnert D, Lee M and **Klier K.** 1995. Genetic mapping of quantitative trait loci for panicle characteristics and seed weight in sorghum. Rev. Brasil. Genet. 18:249–257.

Pillonel C, Moulderm, Boon J, Foster B and **Binder A.** 1991. Involvement of cinnamylalcohol dehydrogenose in the control of lignin formation in *Sorghum bicolor* (L.) Moench. Planta 185:538–544.

Porter KS, Axtell JD, Lechtenberg VL and **Colenbrandu VF.** 1978. Phenotype fiber composition and *in vitro* dry matter disappearance of chemically induced brown – midrib (*bmr*) mutants of sorghum. Crop Sci. 18:205–209.

Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CCA, Frederick WJ, Jr., Hallett JP, Leak DJ, Liotta CL, Mielenz JR, Murphy R, Templer R and **Tschaplinski T.** 2006. The path forward for biofuels and biomaterials. Science 311:484–489.

Rajashekar MK. 2007. Studies on heterosis, combining ability,stability and molecular diversity in sweet sorghum [Sorghum bicolor (L) Moench]. PhD Thesis submitted to University of Agricultural Sciences, Dharwad, Karnataka, India, Pp. 265.

Rajendran C, Ramamurthy K and **Backivarani CK**. 2000. Effect of deheading on juice quality characteristics and sugar yield of sweet sorghum. J. Agronomy and Crop Science 185:23–26.

Rajvanshi AK and **Nimbkar N.** 1996. Sweet sorghum R&D at the NARI. *In* Procedings of the First European Seminar on Sorghum for Energy and Industry, Toulouse, France, 1–3, April 1996.

Rami JF, Dufour P, Trouche G, Fliedel G, Mestres C, Davrieux F, Blanchard P and **Hamon P.** 1998. Quantitative trait loci for grain quality, productivity, morphological, and agronomical traits in sorghum [*Sorghum bicolor* L. Moench]. Theor. Appl. Genet. 97:605–616.

Rao DB, 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. Rajendranagar, Hyderabad 500 030, Andhra Pradesh, India: National Research Centre for Sorghum. Pp. 20.

Ratanavathi CV, Dayakar Rao B and **Seetharama N.** 2003. Sweet sorghum stalk: A suitable raw material for fuel alcohol production. DSR/NRCS Report Number-12/2003. NATP (DSR) Series No. 1. Rajendranagar, Hyderabad 500 030, Andhra Pradesh, India: National Research Center for Sorghum (NRCS). Pp. 8.

Reddy BVS and **Sanjana Reddy P.** 2003. Sweet sorghum: Characteristics and potential. International Sorghum and Millets Newsletter 44:26–28.

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

Reddy BVS, Srinivasa Rao P, Ashok Kumar A, Sanjana Reddy P, Parthasarathy Rao P, Sharma KK, Blummel M and **Reddy Ch Ravinder.** 2009. Sweet sorghum as a biofuel crop: Where are we now? Pages 191–202 *in* Proceedings of the Sixth Int. Biofuels Conference, 4–5 March 2009, New Delhi. Winrock International.

RFA. 2009. Building new horizons: Ethanol industry outlook 2007. Washington DC: Renewable Fuels Association.

Ritter KB, McIntye CL, Godwin ID, Jordan DR and **Chapman SC.** 2007. An assessment of the genetic relationship between sweet and grain sorghums, within *Sorghum bicolor* ssp. bicolor (L.) Moench, using AFLP. Euphytica 157:161–167.

Royal Society Policy Document. 2008. Sustainable biofuels: Prospects and challenges. Cardiff, UK: The Clyvedon Press Ltd..ISBN 978 0 85403 662 2.

Saballos A, Ejeta G, Sanchez E, Kang C and **Vermerris W** 2009. A genomewide analysis of the cinnamyl alcohol dehydrogenase family in sorghum [*Sorghum bicolor* (L.) Moench] identifies SbCAD2 as the Brown midrib 6 gene. Genetics 181: 783–795 **.**

Saballos A, Vermerris W, Rivera L and **Ejeta G.** 2008. Allelic association, chemical characterization and saccharification properties of brown midrib mutants of sorghum [*Sorghum bicolor* (L.) Moench]. Bioenerg. Res. 1:193–204.

Sanchez-Gomez A. 2002. Identification of quantitative trait loci for grain yield in a recombinant inbred B-line population in sorghum. PhD dissertation. Texas A&M University, College Station, Tx., USA.

Sankarapandian R, Ramalingam J, Pillai MA and **Vanniarajan C.** 1994. Heterosis and combining ability studies for juice yield related characteristics in sweet sorghum. Ann. Agric. Res. 15(2):199–204.

Sarath G, Mitchell RB, Sattler SE, Funnell D, Pedersen JF, Graybosch RA and **Vogel KP.** 2008. Opportunities and roadblocks in utilizing forages and small grains for liquid fuels. J Ind Microbiol Biotechnol. doi:10.1007/s10295-007-0296-3.

Satish K, Srinivas G, Madhusudhana R , Padmaja PG, Nagaraja Reddy N, Murali Mohan S and **Seetharama N.** 2009. Identification of quantitative trait loci for resistance to shoot fly in sorghum [*Sorghum bicolor* (L.) Moench]. Accepted in Theor Appl Genet. http://www.springerlink.com/content/d88613421852561w/

Schaffert RE and **Gourley LM.** 1982. Sorghum as energy source. Pages 605–623 *in* Proceedings of the International Symposium on Sorghum, 2–7 November 1981, ICRISAT, Patancheru, AP, India. Patancheru 502 324, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics.

Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D and **Yu T.** 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319.(5867):1238–1240.

Seetharama N, Dayakar Rao B, Ratnavathi CV, Shahid Parwez Md, Binu Mathew and **Bharath Kumar KA**. 2002. Sorghum as a raw material for alcohol production. Presented at the seminar on Current Development in Alcohol Industry organized by Distillers' Association of Maharashtra, 25 August 2002, Sahar, Mumbai, India.

Seetharama N, Prasad Rao KE, Subramanian Vaidyanathan and **Murthy DS**. 1987. Screening for sweet stalk sorghum and environmental effect on stalk sugar concentrations. Pages 169-179 *in* Procedings of National Seminar Technology and Application for Alternate Uses of Sorghum, 2–3 February 1987, MAU, Parbhani, Maharahtra, India

Segundo U Bruno JRA and **Boddey RM**. 2005. Produção de bio-combustiveis: A questão do balanço enrgetico. Rev. Política Agric. 5:42–46.

Selvi B and **Palanisamy S.** 1990. Heterosis and combining ability for grain yield in sweet sorghum. Madras Agricultural Journal 77:493–496.

Sewalt VJH, Ni W, Blount JW, Jung HG, Howles PA, Masoud S, Lamb C and Dixon RA. 1997a. Reduced lignin content and altered lignin composition in transgenic tobacco down-regulated in expression of phenylalanine ammonia-lyase or cinnamate 4-hydroxylase. Plant Physiol 115: 41–50.

Sewalt VJH, Ni W, Jung H and Dixon RA. 1997b. Lignin impact on fiber degradation: increased enzymatic digestibility of genetically engineered tobacco (*Nicotiana tabacum*) stems reduced in lignin content. J Agric Food Chem 45:1977–1983 **.**

Shadle G, Chen F, Srinivasa Reddy MS, Jackson L, Nakashima J and **Dixon RA**. 2007. Down-regulation of hydroxycinnamoyl CoA: shikimate hydroxycinnamoyl transferase in transgenic alfalfa affects lignification, development and forage quality. Phytochemistry 68:1521–1529.

Shapouri H and **McAloon A.** 2004. The (2001) net energy balance of corn ethanol. Available at www.usda.gov/oce/reports/energy/ net_energy_balance.pdf (verified 8 October 2007). Washington, DC: USDA, Office of the Chief Economist.

Shapouri H, Duffield JA and **Wang M.** 2002. The energy balance of corn ethanol: An update. USDA, Office of Energy Policy and New Uses, Agricultural Economics., Report No. 813. 14 p.

Singh K and **Singh B**. 1986. Sweet sorghum–An ancillary sugar crop. Indian Farming 36(4):7–8.

Smith AM. 2008. Prospects for increasing starch and sucrose yields for bioethanol production. The Plant Journal 54:546–558.

Smith GA and **Buxton DR.** 1993. Temperate zone sweet sorghum ethanol production potential. Bioresource Technol., 43: (1) 71-75.

Somerville C. 2006. The billion-ton biofuels vision. Science 312:1277.

Somerville C. 2007. Biofuels. Curr Biol. 17(4):9.

Spatari S, Zhang Y and **MacLean HL.** 2005. Life cycle assessment of switchgrass- and corn stover-derived ethanol-fueled automobiles. Environ. Sci. Technol. 39(24): 9750–9758.

Steenblik R. 2007. Biofuels–At what cost? Government support for ethanol and biodiesel in selected OECD countries. A Synthesis of Reports Addressing Subsidies for Biofuels in Australia, Canada, the European Union, Switzerland and the United States. The Global Subsidies Initiative of the International Institute for Sustainable Development, Geneva, Switzerland, September 2007.

Sticklen MD. 2008. plant genetic engineering for biofuel production: Towards affordable cellulohic ethanol.Nature Genetics 9:433-443.

Subudhi PK and **Nyugen HT.** 2000. New horizons in biotechnology. Pages 349–398 *in* Sorghum: Evolution, History, Production and Technology (Smith CW and Frederiksen RA, eds.). New York: Wiley.

Subudhi PK, Rosenow DT and **Nguyen HT.** 2000. Quantitative trait loci for the stay green trait in sorghum (*Sorghum bicolor* L. Moench): Consistency across genetic background and environments. Theor. Appl. Genet. 101:733–741.

Sumantri A and **Edi Purnomo.** 1997. Sweet sorghum research and development in Indonesia. Pages 49–54 *in* Proceedings of the First International Sweet Sorghum Conference, 14–19 September 1997, Beijing, China (Li Dajue, ed.). Beijing, China: Institute of Botany, Chinese Academy of Sciences.

Sutter C. 2003. Sustainability Check-Up for CDM Projects: Multi-Criteria Assessment of Energy Related Projects Under the Clean Development Mechanism of the Kyoto Protocol. Berlin, Wissenschaftlicher Verlag Berlin (ISBN: 3-936846-59-6)

Tao YZ, Hardy A, Drenth J, Henzell RG, Franzmann BA, Jordan DR, Butler DG and **McIntyre CL.** 2003. Identifications of two different mechanisms for sorghum midge resistance through QTL mapping. Theor. Appl. Genet. 107:116–122.

Tao YZ, Henzell RG, Jordan DR, Butler DG, Kelley AM and **McIntyre CL.** 2000. Identification of genomic regions associated with stay green in sorghum by testing RILs in multiple environments. Theor. Appl. Genet. 100:1225–1232.

Tao YZ, Jordan R, Henzell RG and **McIntyre CL.** 1998. Identification of genomic regions for rust resistance in sorghum. Euphytica, 103: 287–292.

Tew TL, Cobill RM and **Richard Jr EP.** 2008. Evaluation of sweet Sorghum and sorghum × sudangrass hybrids as feedstocks for ethanol production. BioEnergy Research.:147–152 .

Tsuchihashi N and **Goto Y.** 2004. Cultivation of sweet sorghum and determination of its harvest time to make use as the raw material for fermentation practical during rainy season in dryland of Indonesia. Plant Production Science 7:442–448.

Tuinstra MR, Grote EM, Goldsborough PB and **Ejeta G.** 1996. Identification of quantitative trait loci associated with pre-flowering drought tolerance in sorghum. Crop Sci. 36:1337–1344.

Tuinstra MR, Grote EM, Goldsborough PB and **Ejeta G.** 1997. Genetic analysis of postflowering drought tolerance and components of grain development in *Sorghum bicolor* (L.) Moench. Mol. Breed. 3:439–448.

UNICA – União da Indústria de Cana de Açúcar. 2006. Available at www.unica.com.br.

UNICA. 2007. As more than a basic element in Brazil's development. Available at http://www.portalunica.com.br/portalunicaenglish/index.php?Secao=sugarcane (verified 30 January 2007). São Paulo, SP, Brazil: União da Indústria de Cana-de-Açucar.

US Census Bureau. 2006. World population information. http://www.census.gov/ipc / www/idb/worldpopinfo.html. Washington, DC: US Census Bureau.

USDOE. 2005. Genomics: GTL roadmap: Systems biology for energy and environment. DOE/SC 0090. Available at http:// genomicsgtl.energy.gov. Washington, DC: USDOE, Office of Science.

Vailhé MAB, Migné C, Cornu A, Maillot MP, Grenet E, Besle TM, Atanassova R, Martz F and **Legrand M.** 1996. Effect of modification of the *O*-methyltransferase activity on cell wallcomposition, ultrastructure and degradability of transgenic tobacco. J Sci Food Agric 72:385–392 .

Vailhé MAB, Besle JM, Maillot MP, Cornu A, Halpin C and **Knight M.** 1998. Effect of down-regulation of cinnamyl alcohol dehydrogenase on cell wall composition and on degradability of tobacco. J Sci Food Agric 76:505–514.

Vermerris W, Saballos A, Ejeta G, Mosier NS, Ladisch MR and **Carpita NC.** 2007. Molecular breeding to enhance ethanol production from corn and sorghum stover. Crop Sci. 47(S3):S142–S153.

Vogler R, Ejeta G, Johnson K and **Axtell J.** 1994. Characterization of a new brown midrib sorghum line. Page 124 *in* Agronomy Abstracts. Madison, WI: ASA.

Wilhelm WW, Johnson JMF, Hatfield JL, Voorhees WB and **Linden DR.** 2004. Crop and soil productivity response to corn residue removal: A literature review. Agron. J. 96:1–17.

Woods J. 2001. The potential for energy production using sweet sorghum in southern Africa. Energy for Sustainable. Development V(1):31–38.

Wu L and **Birch RG.** 2007. Doubled sugar content in sugarcane plants modified to produce a sucrose isomer. Plant Biotechnol. J. 5:109–117.

Wu YQ and **Huang Y.** 2007. An SSR genetic map of *Sorghum bicolor* (L.) Moench and its comparison to a published genetic map. Genome 50:84–89.

Wyman CE, Dale BE, Elander RT, Holtzapple M, Ladisch MR and **Lee YY.** 2005. Coordinated development of leading biomass pretreatment technologies. Bio-resource Technology 96:1959–1966.

Xin Z, Wang ML, Burow G and **Burke J.** 2009. An induced sorghum mutant population suitable for bioenergy research. Bioenergy Res. 2:10–16.

Xu Li, Weng JK and **Chappale C.** 2008. Improvement of biomass through lignin modification. The Plant Journal 54:569–581.

Xu WW, Subudhi PK, Crasta OR, Rosenow DT, Mullet JE and **Nguyen HT.** 2000. Molecular mapping of QTLs conferring stay green in sorghum. Genome 43:461–469.

Yan W and **Kang MS.** 2003. GGE biplot analysis: A graphical tool for breeders, geneticists, and agronomists. Boca Raton, FL: CRC Press.

Yan W, Kang MS, Ma B, Woods S and **Cornelius PL.** 2007. GGE Biplot vs AMMI analysis of genotype-by-environment data. Crop Sci. 47:643–653.

Yan W. 2001. GGE biplot: A windows application for graphical analysis of multi-environment trial data and other types of two-way data. Agron. J. 93:1111–1118.

Yong W, Link B, O'Malley R, Tewari J, Hunter CT, Lu CA, Li X, Bleecker AB, Koch KE, McCann MC, McCarty DR, Patterson SE, Reiter WD, Staiger C, Thomas SR, Vermerris W and **Carpita NC.** 2005. Genomics of plant cell wall biogenesis. Planta 221:747–751.

Yun-long B, Seiji Y, Maiko I and **Hong-wei C.** 2006. QTLs for sugar content of stalk in sweet sorghum. Agricultural Sciences in China 5(10):736–744.

Zhao YL, Dolat A, Steinberger Y, Wang X, Osman A and **Xie GH**. 2009. Biomass yield and changes in chemical composition of sweet sorghum cultivars grown for biofuel. Field Crops Res. 111:55−64.

Zhu Cuiyun. 1998. Review and perspective on sweet sorghum breeding in China. International Sorghum and Millets Newsletter 9:70−71.

About ICRISAT

The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) is a non-profit, non-political organization that does innovative agricultural research and capacity building for sustainable development with a wide array of partners across the globe. ICRISAT's mission is to help empower 600 million poor people to overcome hunger, poverty and a degraded environment in the dry tropics through better agriculture. ICRISAT is supported by the Consultative Group on International Agricultural Research (CGIAR).

Contact Information

ICRISAT-Patancheru
(Headquarters)
Patancheru 502 324
Andhra Pradesh, India
Tel +91 40 30713071
Fax +91 40 30713074
icrisat@cgiar.org

ICRISAT-Liaison Office
CG Centers Block
NASC Complex
Dev Prakash Shastri Marg
New Delhi 110 012, India
Tel +91 11 32472306 to 08
Fax +91 11 25841294

ICRISAT-Nairobi
(Regional hub ESA)
PO Box 39063, Nairobi, Kenya
Tel +254 20 7224550
Fax +254 20 7224001
icrisat-nairobi@cgiar.org

ICRISAT-Niamey
(Regional hub WCA)
BP 12404, Niamey, Niger (Via Paris)
Tel +227 20722529, 20722725
Fax +227 20734329
icrisatsc@cgiar.org

ICRISAT-Bamako
BP 320
Bamako, Mali
Tel +223 20 223375
Fax +223 20 228683
icrisat-w-mali@cgiar.org

ICRISAT-Bulawayo
Matopos Research Station
PO Box 776,
Bulawayo, Zimbabwe
Tel +263 83 8311 to 15
Fax +263 83 8253, 8307
icrisatzw@cgiar.org

ICRISAT-Lilongwe
Chitedze Agricultural Research Station
PO Box 1096
Lilongwe, Malawi
Tel +265 1 707297, 071, 067, 057
Fax +265 1 707298
icrisat-malawi@cgiar.org

ICRISAT-Maputo
c/o IIAM, Av. das FPLM No 2698
Caixa Postal 1906
Maputo, Mozambique
Tel +258 21 461657
Fax +258 21 461581
icrisatmoz@panintra.com

www.icrisat.org

ISBN: 978-92-9066-518-2 Order code: IBE 077 295-2009