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Bio-Fuel Crops Research for Energy Security and Rural Development in Developing Countries

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Abstract Soaring prices of fossil fuels, geo-political issues and environmental pollution associated with fossil fuel use has led to worldwide interest in the production and use of bio-fuels. Both the developed and developing countries have developed a range of policies to encourage production of combustible fuels from plants that triggered public and private investments in bio-fuel crop research and development, and bio-fuels production. In this article, we discuss the potential benefits of bio-fuels in increasing the farmers' incomes, reducing environment pollution, the crop options and research and development interventions required to generate feedstocks to produce bio-fuels to meet projected demand without compromising food/fodder security in developing countries.

Keywords Agriculture research · Energy security · Bio-fuel · Ethanol · Bio-diesel

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The United Nations (UN) Millennium Development Goals (MDGs) provide a blueprint for improving livelihoods (alleviate poverty), and preserving natural resources and the environment with 2015 as target date. None of the MDGs however, has a specific reference to energy security, though energy is the fuel of economic prosperity that is essential for alleviating poverty. Nonetheless, diversifying crop uses, identifying and introducing bio-fuel crops would lead to enhanced farmers' incomes, thereby contributing to *eradicating extreme poverty* (MDG 1) in rural areas, helping 75% of the world's 2.5 billion poor (who live on <US$ 2 per day), and contributing to the environmental protection. Energy is required for consumptive uses (cooking, lighting, heating, and entertainment), social needs (education and health care services), public transport (road, rail and air), industries, and agriculture and allied sectors. 'Energizing' the agriculture production chain is critical to achieve food security, considering strong correlation between per capita energy consumption and crop yields in both developed and developing countries.

Fossil fuels do not provide equitable economic and environment-friendly benefits. Biofuels, produced from selected agricultural biomass, among other renewable sources provide sustainable and eco-friendly energy options that foster *environmental sustainability* (MDG 7) and offer opportunities to improve the income level of developing world's smallholder subsistence farmers who depend on agriculture for their livelihoods. However, not all crops offer equal environmental advantages. The crop, cultivar and production system and the processing technology are critical. Biofuel research-for-development will lead to new local, regional and national public-private *partnerships for development* (MDG 8).

Policy support and the availability of efficient biomass (feedstock) energy conversion technologies are the key factors that could foster market forces for, and cost-competitiveness of bio-fuels vis-à-vis fossil-fuels. However, generation of huge volumes of quality feedstocks to produce bio-fuel to meet the projected demand without compromising food and fodder security requires massive investments and reorientation of research on crops used for bio-fuel production. In this article, we discuss the opportunities and the role of selected biofuel crops for mitigating tradeoffs between food/fodder and energy security and the potential benefits of bio-fuels in alleviating poverty and contribution to environmental sustainability.

Current Scenario for Bio-Fuels

Bio-fuels are currently based on the production of ethanol from sugars or starch and production of bio-diesel from edible and non-edible plant oils and animal fats. Ethanol (projected at 61 billion liters in 2008, http://www.marketresearchanalyst.com/2008/01/26/world-ethanol-production-forecast-2008-2012/, verified on March 24, 2008) accounted for about 90% of total world bio-fuel production. USA (24.5×10^9 l in 2007, http://www.ethanolrfa.org/industry/statistics/, verified on March 24, 2008) and Brazil (18.2×10^9 l in 2006) are the largest producers of ethanol [28]. Taking cue from Brazil and the USA, several developed and developing countries are making concerted efforts to reduce their dependence on oil imports and reduce greenhouse gas (GHG) emission levels through policies to produce bio-ethanol and bio-diesel for blending with fossil fuels [10]. Many a countries use molasses from sugarcane (*Saccharum officinarum*) to produce ethanol. However, large fluctuations in the quantity of production and price of molasses not only result in inadequate supply to produce sufficient ethanol to meet the current and future requirements but also make molasses expensive for use in ethanol production.

Bio-diesel can be produced from edible oilseeds from crops such as soybean (*Glycine max* L.), rapeseed (*Brassica* spp.) or sunflower (*Helianthus annuus* L.). However, given the large gap between the demand and supply of edible oils, many countries cannot afford to use vegetable oils for bio-diesel production. Fortunately, bio-diesel can also be produced from non-edible oilseeds from shrubs such as jatropha (*Jatropha curcus*), pongamia (*Pongamia pinnata*) and neem (*Azadirachta indica*). Though higher yields are expected planting non-edible oilseeds for bio-diesel it is not advisable in areas meant for food crops. These crops should be promoted on wastelands and field bunds taking appropriate steps for preventing land/environmental degradation.

Table 1 Economics of sweet sorghum production in India (ha^{-1}) under rain fed conditions (750 mm rainfall)

	Sweet sorghum	Grain sorghum
Grain yield (Mg ha^{-1})	1.6	2.5
Stalk yield (Mg ha^{-1})	20	4 (dry)
Grain value (US$ season^{-1})	234	365
Stalk value (US$ season^{-1})	293	50
Total value (US$ season^{-1})	527	415
Leaf stripping (US$ season^{-1})	−15	–
Net value (US$ season^{-1})	512	415
Gain from sweet sorghum (US$ season^{-1} ha^{-1})	97 (23%)	

Potential Benefits of Bio-Fuels

As bio-fuels can be produced from biomass of crop plants, they offer opportunities to improve the income levels of smallholder farmers. At a community level, farmers can cultivate energy crops that fetch an income while also meeting their food needs. For example, a dry land farmer can get 23% extra income [19] from sweet sorghum [*Sorghum bicolor* (L.) Moench] in the place of grain sorghum crop (Table 1) while continuing to meet their food needs. The leaves, panicle residues and the bagasse (crushed stalk after extraction of juice) from sweet sorghum form excellent animal feed. Given the bulkiness of most of the feedstocks, it is necessary to locate bio-fuel industries in rural areas where the feedstock crops are grown in order to reduce the need for transportation. Technologies for reducing the feed stock volume (e.g. decentralized syrup units supplying syrup to the distillery instead of the voluminous stalks) need to be given major thrust. Local production of bio-fuels is projected to have a broad range of positive economic, social and environmental implications.

As bio-fuels are renewable, non-toxic and biodegradable, they contribute to energy security and reducing environment pollution. The use of even 10% ethanol blends reduces GHG emissions by 12 to 19% compared with conventional fossil fuels. Burning E 85 (85% ethanol) reduces the Nitrogen oxide emissions by 10% compared to conventional gasoline (Table 2). Ethanol can be blended in low proportions up to 25%, with petrol for use in normal

Table 2 Emission characteristics: potential benefits offered by E 85, relative to conventional gasoline

Reductions in particulate emissions	20%
Reductions in nitrogen oxide emissions	10%
Reductions in sulphate emissions	80%

Source: http://eerc.ra.utk.edu/etcfc/docs/EPAFactSheet-ethanol.pdf, verified on March 24, 2008 internal combustion engines without modification. Similarly, use of diesel blended with fossil-diesel up to 20% (B 20) results in substantial reduction of un-burnt hydrocarbons (by 30%), carbon monoxide (by 20%) and particulate matters (by 25%) and negligible sulfur content in the emissions and requires very little or no modification of engine [11]. Bio-diesel can be directly used to run power-drawn implements, tractors, pump sets for lift irrigation, and vehicles to transport agriculture produce to the markets. Tribal communities in Andhra Pradesh (India) are using straight pongamia oil for running diesel generator sets to produce electricity in villages [30].

Crop-Improvement Research to Address Bio-Fuel Needs

Most of the developing nations, including China and India, have plans to double their bio-fuel production within the next 15 years. Meeting this target without compromising food and fodder security requires reorientation of agricultural research. This encompasses careful selection among the existing bio-ethanol and bio-diesel feedstock crop species, introducing new crop species, and their genetic and production management to improve their energy value. The most promising crop options and the researchable issues need to be addressed for more efficient bio-ethanol and bio-diesel production.

Ethanol

Though sugarcane and corn are the major feed stocks currently used for ethanol production, their potential is limited to irrigated (or high rain fall) and well endowed environments. Further, the use of corn for ethanol production compromise with the food security in developing countries. Hence, they are kept outside the purview.

Sweet Sorghum [*Sorghum bicolor* (L.) Moench]

Sweet sorghums, which are similar to grain sorghums but feature more rapid growth, higher biomass production, and wider adaptation, have good potential for ethanol production [22]. Sweet sorghum can be readily cultivated in semi-arid tropics as the farmers are quite familiar with grain sorghum crop cultivation. The dual-purpose nature of sweet sorghums—they produce both grain and sugar-rich stalks—offers new market opportunities for smallholder farmers and does not threaten food trade for sorghum as farmers harvest grain while selling the stalks to industry for ethanol production. Sorghum has been cultivated for centuries in several African countries, China and India. Incidentally, most of the landraces that are being grown in India in postrainy season (NTJ 2, S-35) are sweet sorghums that are suitable for ethanol production. In West Africa, sweet sorghums are chewed just like sugarcane owing to their high sweetness. The emerging bio-fuel needs, therefore offer expanded markets for sweet sorghum in India, China, USA, Australia and several African countries [25, 31, 12]. As sweet sorghum requires less water and has a higher fermentable sugar content than sugarcane (which contains more crystallizable sugars), it is better suited for ethanol production than sugarcane [22]. Also, sweet sorghum-based ethanol is sulphur-free and cleaner than molasses-based ethanol, when mixed with gasoline. Pilot studies in India indicated that ethanol production from sweet sorghum is cost-effective (Table 3).

Currently, sugarcane molasses is the main raw material for ethanol production in India, China and other developing countries. Sweet sorghum growing period (about 4.5 months) and water requirement (8,000 m^3 over two crops) [26] are four times lower than those of sugarcane (12−16 months duration and 36,000 m^3 of water per crop). Sweet sorghum juice is better suited for ethanol production because of its higher content of reducing sugars as compared to other sources including sugarcane juice. The

Table 3 Comparative advantages of sweet sorghum vs. sugarcane/sugarcane molasses for ethanol production in India

Crop	Cost of cultivation (USD ha^{-1})	Crop duration (months)	Water requirement (m^3)	Ethanol productivity (l ha^{-1})	Cost of ethanol production (USD l^{-1})
Sweet sorghum	435 over two crops	4.5	8,000 over two crops	4,000 $year^{-1}$ over two crops[a]	0.32[b]
Sugarcane	1,079 $crop^{-1}$	12–16	36,000 $crop^{-1}$	6,500 $crop^{-1}$ [c]	
Sugarcane molasses	–	–	–	850 $year^{-1}$ [d]	0.37[e]

[a] 50 Mg ha^{-1} millable stalk per crop at 40 l t^{-1}
[c] 85–90 Mg ha^{-1} millable cane per crop at 75 l^{-1}
[d] 3.4 Mg ha^{-1} at 250 l t^{-1}
[b] Sweet sorghum stalk at US$ 12.2 Mg^{-1}
[e] Sugarcane molasses at US$ 39 Mg^{-1}
Source: Dayakar Rao et al. [9]

water use efficiency [14, 8] along with its suitability for seed propagation, mechanized crop production, and comparable ethanol production capacity vis-à-vis sugarcane molasses and sugarcane makes sweet sorghum a viable alternative raw material source for ethanol production (Table 3). Also, the ethanol production from sweet sorghum is more economical as compared to sugarcane molasses at the prevailing prices.

In addition to sweet stalks, grain yield of 2 to 2.5 t ha^{-1} can be obtained from sweet sorghum that can be used as food or feed. The bagasse (stalks after crushing) from sweet sorghum after the extraction of juice has a higher biological value than the bagasse from sugarcane when used as feed for cattle, being rich in micronutrients and minerals.

Livestock Digestibility Studies with Sweet Sorghum Bagasse Sweet sorghum bagasse was compared with normal stover in the commercial blocks for daily intake and weight gain in large ruminants (bullocks) in a randomized block design with three replications for 40 days. Comparison of commercial feed blocks (normal sorghum stover + concentrates, 50:50 by weight) with bagasse block (normal sorghum replaced by bagasse while the concentrates remained the same) and sorghum stover alone showed no significant differences in intake and body weight gain between bagasse block and commercial feed block (Table 4). The results have clearly indicated that sweet sorghum bagasse after extraction of the juice can be used as animal feed without any reduction in daily intake or weight gain. This will pave way for the effective whole plant utilization of sweet sorghum. Preliminary results from experiments involving sheep at International Livestock Research Institute (ILRI) vindicated these findings.

Sweet Sorghum Research at ICRISAT

BioPower Strategy To find ways to empower the poor of dry lands to benefit from, rather than be marginalized by the bio-energy revolution, ICRISAT has launched a global BioPower Initiative. BioPower is a pro-poor strategy that focuses on feedstock sources and approaches that do not compete with food production rather produce food as well as fuel and even enhance food production by stimulating increased input use and crop management intensity.

Cultivars ICRISAT initiated the sweet sorghum breeding in 1980 for forage purposes. Two high sugar and biomass yielding germplasm accessions IS 6872 (Sudan) and IS 6896 (origin not known) were identified from screening of 70 germplasm accessions in 1981. From 1990 to till to date 65 germplasm accessions from 17 countries screened (Sudan 12; Ethiopia 11; Kenya 9; Cameroon 6; India 6 and rest others) and selected 27 high biomass accessions with soluble solids (^{0}Bx) 15.5–24.9. In the same period 185 R-lines were screened and 48 lines were selected (^{0}Bx: 10–23). The soluble solid concentration in juice is measured with a hand-held refractometer. Similarly 659 B- lines were screened and 50 promising B-lines were selected (^{0}Bx 9–19). For development of improved R-lines, 366 crosses were made involving 104 parents and 95 promising R-lines are under evaluation. In addition, 182 segregating lines are at hand. Similarly for the improvement of B-lines, 152 crosses were made using 56 parents and 95 promising lines were selected. From this program, 182 segregating lines are at hand. In the hybrid development program, a total of 489 hybrids were tested and Thirty-three hybrids for rainy season and 90 hybrids for postrainy season are in advanced testing. The Pedigree method of breeding was followed for the development of improved lines, and based on the maintainer or restorer reactions, the lines were converted to female lines (A-lines) through backcross breeding involving appropriate cytoplasmic male sterile (CMS) germplasm. The number of open pollinated cultivars /A-/B-lines and hybrids transferred to different countries by ICRISAT from 1990 to 2007 are presented in Table 5.

Several NARS and ICRISAT-bred improved sweet sorghum lines with high stalk sugar content that are currently being tested in pilot studies for sweet sorghum-based ethanol production in India, the Philippines and Uganda. A few of these cultivars like SSV84, SSV74 and CSH22SS (ICSA38 × SSV84) have been released in India. The cultivar NTJ2 is currently used for ethanol production by Rusni distilleries in Andhra Pradesh. Some of the cultivars or restorer lines developed with soluble solids (^{0}Bx) greater than 19% are ICSR93034, ICSV700, ICSV93046, E36-1, SPV422, NTJ2,

Table 4 Intake and body weight gain for different feed blocks

Treatment	Intake (g kg^{-1} live weight)	Weight gain (kg day^{-1})
Commercial feed block	3.64	0.975
Bagasse-leave feed block	3.76	0.871
Sorghum stover (chopped)	1.24	−0.457

Source: Michael Blümmel et al. (unpublished)

Table 5 Particulars of open pollinated cultivars/A-/B-lines /hybrids transferred by ICRISAT

Region	Open pollinated cultivars	A-/B-lines	Hybrids
India	403 (91)[a]	51 (5)	307 (6)
The Philippines	131 (10)	10 (1)	88 (2)
Africa	294 (21)	12 (2)	176 (4)
Others	234 (30)	24 (4)	0 (0)

[a] Figures in parentheses are the number of consignees

Table 6 Performance of sweet sorghum cultivars at MMSU, Ilocos Norte, The Philippines

Cultivar	Stripped stalk yield (Mg ha^{-1})		Grain yield (Mg ha^{-1})		Soluble solid concentration (^{0}Bx)
	Main crop	Ratoon crop	Main crop	Ratoon crop	
NTJ2	48	52	3.62	4.40	18.5
SPV422	58	61	3.28	3.92	19.0
ICSV700	45	48	3.46	4.11	18.0
ICSV93046	50	52	3.40	4.08	15.0
ICSR93034	49	50	3.46	4.25	18.0

Seredo and Entry #64 DTN [22, 20, 21]. Some of the promising female lines for combining ability for high soluble solids are ICSA/B38, ICSB264, ICSA/B 474, 321, 480, 479, 453, 73, 271 and 487. Of late the major focus is on development of high sugar and grain yielding hybrids.

The mean performance of some of the ICRISAT developed sweet sorghum cultivars (in a replicated trial, randomized complete block design (RCBD) with three replications) in Mariano Marcos State University (MMSU, Ilocos Norte, Philippines) over two years is given in Table 6. Following this testing, SPV422 was selected by Philippines' national program.

Hybrids Research experience at ICRISAT and elsewhere has shown that hybrids produce relatively higher biomass, mature earlier and are more photoperiod-insensitive compared to open pollinated cultivars under normal as well as abiotic stresses, including water-limited environments. The photoperiod- and temperature-insensitiveness is essential to facilitate plantings at different dates for continuous supply of sweet sorghum stalks to distilleries for ethanol production. Therefore, the development of sweet sorghum hybrids is receiving high priority to produce more feedstock and grain yield. The mean performance of selected sweet sorghum hybrids (in a RCBD trial with 3 replications) over two seasons are presented in Table 7.

Season-Specificity in Hybrids Some of the hybrids do well in the rainy season and others in postrainy season at Patancheru (Andhra Pradesh) in India. Therefore it appears that selection of the hybrids is season specific (Table 8).

Photoperiod- and Temperature-Sensitivity of Hybrids Versus Open Pollinated Cultivars

Sweet sorghum hybrids and open pollinated cultivars were sown at different dates (representing different photoperiods and soil and air temperatures) during November 2004 to March 2006 at ICRISAT, Patancheru to evaluate them under different photoperiods and thermo-sensitivity in a RCBD with 3 replications. Data were recorded for days to 50% flowering in all the genotypes sown at different sowing dates. The results clearly showed that the hybrids matured earlier than open pollinated cultivars. Also variation in days to 50% flowering of hybrids was minimal compared to those of open pollinated cultivars sown in different dates (Fig. 1) indicating relatively less photoperiod- and temperature-sensitiveness of hybrids. The photoperiod- and temperature-insensitiveness is required to predict maturity period, which in turn helps in timely scheduling the supply of sweet stalks to distillery units as and when required.

Considering all aspects—early maturity, high biomass, ethanol and grain yield potential and photoperiod-and thermo-insensitivity of hybrids vis-à-vis open pollinated cultivars, the hybrids approach is the best option for sweet sorghum-based ethanol production technology [20, 21].

Table 7 Performance of selected sweet sorghum hybrids at ICRISAT, Patancheru, India

Hybrid	Days to 50% flower	Soluble solid concentration (^{0}Bx)	Cane yield (Mg ha^{-1})	Juice yield (kl ha^{-1})	Sugar yield (Mg ha^{-1})	Grain yield (Mg ha^{-1})	Per day ethanol productivity (l ha^{-1})[a]
ICSA749 × SSV74	85	18.00	57.75	27.15	9.15	3.28	18.48
ICSA511 × SSV74	88	17.97	49.25	22.7	7.84	5.79	15.39
ICSA474 × SSV74	82	16.33	52.25	25.42	7.57	7.19	17.13
SSV84 (control)	94	15.65	35.18	16.84	4.98	2.67	10.50
NSSH104 (control)	91	15.65	35.17	16.84	4.98	4.12	10.74

[a] Ethanol productivity estimated at 40 liters per ton of millable cane yield.

Table 8 Selected sweet sorghum hybrids performance in rainy season and postrainy season for soluble solid concentration (⁰Bx), sugar yield in stalks and grain yield (2 years and two seasons testing)

Hybrid	Soluble solid concentration (^{0}Bx)		Sugar yield (Mg ha^{-1})[a]				Grain yield (Mg ha^{-1})			
	R[b]	PR[c]	*R*	Rank	PR	Rank	*R*	Rank	PR	Rank
ICSA675 × SSV74	16.6	10.3	6.3	1	1.1	9	6.7	8	7.1	8
ICSA675 × SPV422	17.3	11.7	6.1	2	0.9	14	6.6	9	6.7	10
ICSA324 × SPV422	16.5	16.1	4.8	13	1.7	2	4.9	17	3.9	20
ICSA474 × E36–1	13.5	14.3	4.8	14	1.7	3	6.3	14	6.2	15
NSSH104 (control)	18.5	19.8	5.9	3	1.2	8	4.2	18	7.2	3

Trial entries: 20; RCBD; 2 years and two seasons testing
[a] Calculated as the product of ^{0}Bx and juice volume (kl ha^{-1})
[b] *R* rainy season
[c] *PR* Postrainy season

Food Versus Fuel Trade-Off It is often stated that sweet sorghum cultivars do not produce grain yield or the grain yield is less. However, at ICRISAT, comparison of sweet sorghum and non-sweet sorghum hybrids in the rainy season showed that the sweet sorghum produce higher sugar yield (21%) and higher grain yield (15%) than non-sweet sorghum hybrids, indicating that there is no yield penalty in sweet sorghum if hybrids are used in rainy season. There was some trade-off in the open pollinated cultivars between higher grain yield and sugar yield, but the loss in grain yield is far less compared to the gain in sugar yield during the rainy season (Table 9). Similar trends were observed for both open pollinated cultivars and hybrids during the postrainy season.

Cassava Cassava (*Manihot esculenta* Crantz), traditionally a staple food crop for millions of people in Africa and Latin America, is widely cultivated in Asia, mainly for industrial uses. It produces an adequate quantity of tuberous root biomass even in low fertility soils. The tuberous roots contain high starch (about 70–85% by dry weight basis), which can be used as raw material for ethanol production. The harvested roots can be readily transformed into dried chips in order to lengthen the storage time of tuberous roots as well as to reduce the biomass volume to facilitate easy transportation. To produce ethanol, the starch is first converted into glucose by enzymes and glucose is then fermented to alcohol by yeast.

Cassava farmers have a great market opportunity now. The removal of large quantities of maize (*Zea mays* L) from the market for subsidized bioethanol production in the USA has changed the world market for industrial starch, opening up a tremendous opportunity for developing countries to grow cassava to supply this market. In addition, new technologies to improve the hydrolysis of starch into glucose (originally developed for maize) are also suitable for cassava. The International Institute of Tropical Agriculture (IITA, Nigeria) and Centro Internacional de Agricultura Tropical (CIAT, Colombia) have developed several early bulking and high yielding cassava cultivars with resistance to major diseases and pests. These improved cassava cultivars need to be introduced and tested to identify most suitable cultivars for different agro-climatic zones of Africa, Asia and Latin America. The development of cultivars with high and stable fresh root productivity (FRY) combined with high dry matter content (DMC) is the first of three strategies to produce feedstocks for a competitive ethanol production from cassava roots. In fact this strategy is also suitable for other uses of cassava for the starch and animal feed industries. There are two other

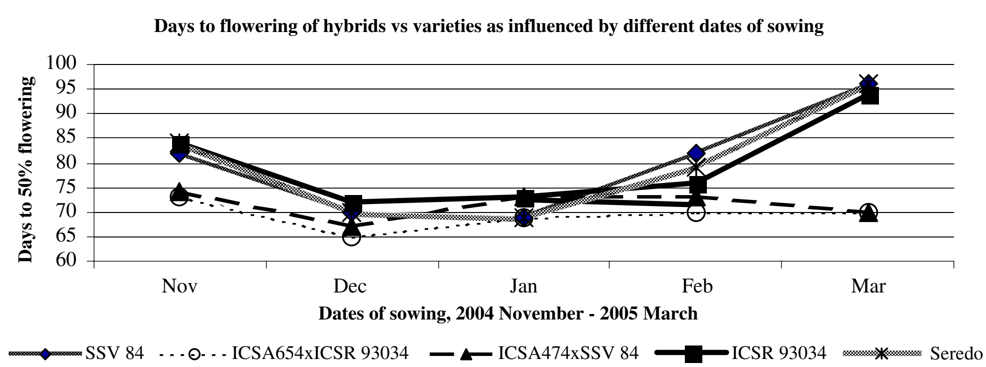

Fig. 1 Response of sweet sorghum hybrids versus open pollinated cultivars in different dates of planting

Table 9 Trade-off between food (grain) and fuel (sugar yield) based on studies at ICRISAT, Patancheru in 2005 and 2006

Season		Stalk sugar yield (Mg ha^{-1})			Grain yield (Mg ha^{-1})		
		Sweet sorghum (SS)	Non-sweet sorghum	Percent gain in SS	Sweet sorghum (SS)	Non-sweet sorghum	Percent gain/loss in SS
Rainy	Open pollinated cultivar	5.8 (7)	4.1 (15)	42	3.4 (7)	4.2 (15)	−18
	Hybrid	5.5 (7)	4.6 (10)	21	7.4 (7)	6.5 (10)	15
Postrainy	Open pollinated cultivar	2.0 (5)	1.3 (17)	53	4.1 (15)	5.2 (17)	−21
	Hybrid	1.6 (6)	0.9 (11)	78	6.0 (6)	7.2 (11)	−16

Numbers in parenthesis indicate number of genotypes used in the study

strategies, specific for ethanol production, that require change in the way cassava research and development is conducted.

The second strategy relies on the production of cultivars with high dry matter productivity per area. The starch and feed industries required high DMC of cassava roots. Low DMC varieties are not acceptable for these industries because they result in higher expenses and effluents in the starch industry or longer drying periods for the production of dried chips used to produce animal feed. However, fresh roots can be used for the production of ethanol and low DMC do not necessarily imply higher production costs. For many years cassava breeders have faced the frustrating and common linkage between high FRY and low DMC. The performance across seven different locations of two half-sib clones (A and B as a simple way to name them) will illustrate this situation. Clone A had a high fresh FRY (42.0 t/ha) compared with that of clone B (29.4 t/ha), but has a lower DMC (31.1%) compared with that of the second clone which had a 36.6% DMC. Clone A was unacceptable for the starch or dried chip industries because, in spite of its high FRY, its DMC was unacceptably low. However, the combination of FRY and DMC results in a 13.1 and 10.8 t/ha of dry matter yield for clones A and B, respectively. Clone A would be much better than clone B for the production of ethanol based on fresh roots, because energy wise it is more productive and its low DMC does not imply higher processing costs.

The third strategy relies on the production of germplasm whose roots will reduce the costs of transformation into ethanol. Several alternatives have been identified. For several years the existence of "sugary" cassava whose roots have distinct water-soluble sugars not present in commercial cultivars are in use [4]. Improvement of biomass of these sugary clones will reduce the cost of ethanol conversion through enhanced efficiency. Currently CIAT is screening the worldwide cassava germplasm collection in search of useful mutants [5]. As a result, an amylose-free mutation that produces waxy starch has been identified [6]. Amylose-free starch should be easier to hydrolyze and, therefore, the costs of conversion into ethanol should be reduced. In addition, an induced mutation that results in starch granules smaller in average size (5.8 μm) compared with normal cassava starch granules (averages ranging from 14.0 to 18.7 μm) has been identified [7]. The granules also offer a rougher surface which, combined with their smaller size, should facilitate the action of starch-degrading enzymes used for the production of ethanol. It is acknowledged, however, that while the starch granule appearance would facilitate bio-ethanol production, the higher proportion of amylose found in this mutation (30% compared with the normal levels of about 20%) would tend to make it less efficient. Only when proper fermentation studies are conducted the relative importance of these contrasting and opposed trends would be clarified. The advantages of these three qualitative traits, which are relevant for their potential impact reducing the costs of transformation of roots into ethanol, should be weighted with the total productivity of energy per unit area once the traits are incorporated into commercial varieties.

Second-Generation Ethanol

Potential Feedstocks The perennial grasses switch grass (*Panicum virgatum L.*) and *Miscanthus* spp. are tipped to be potential sources for second generation (lignocellulosic) ethanol production. Sorghum and maize stover can provide an abundant alternative source of fermentable sugars through enzymatic hydrolysis. While production of cellulosic ethanol from stover is feasible from an energy-balance perspective, its production is currently not economically competitive. Improvements in bio-processing, enhancing the yield and composition of the biomass have the potential to make ethanol production considerably more cost effective. This approach requires (1) better understanding of how cell wall composition and structure affect the efficiency of enzymatic hydrolysis, (2) the development of traits that enhance biomass conversation efficiency and increase biomass yield, and (3) the development of rapid screening protocols to evaluate biomass conversion efficiency. Good number of genetic resources, published work is available to improve sorghum as a lignocellulosic biomass source [18, 29, 28]. This includes the use of existing mutants, generation of new mutants using forward and reverse genetics and transgenic approaches in which the expression of genes of interest is modified. The biomass yield, biomass quality, and biomass conversion efficiency can be improved using appropriate plant breeding/biotechnology tools [28].

Currently, a few countries with higher biomass availability are producing ethanol from lignocellulosic feedstocks [1]. The stovers contain lignin, hemicellulose, and cellulose. The hemi-cellulose, and cellulose are enclosed by lignin (which contains no sugars), making them difficult to reach and convert them into ethanol and hence energy requirement also escalates in this process. Brown midrib mutants of maize [15, 3, 13, 28] and sorghum [18] have significantly lower levels of lignin content (by 51% in stems and by 25% in leaves in sorghum, and by 5 to 50% in maize stems) than those of normal counterparts.

Brown Midrib Sorghum Brown midrib (*bmr*) mutants of sorghum were first developed at Purdue University via chemical mutagenesis [18]. Since then additional spontaneous brow midrib mutants have been identified [29]. Both groups of brown midrib mutants, numbered consecutively 1 though 28, showed altered cell wall composition, particularly relative to lignin subunit composition, and some have superior forage quality. Research at Purdue University indicated 50% higher yield of fermentable sugars from certain maize and sorghum brown midrib mutants' stover after enzymatic hydrolysis [28]. The use of biomass from brown midrib crop cultivars as feedstocks would therefore reduce the cost of ethanol production, thereby making the price of ethanol competitive to that of fossil-fuels. Also, considering that brown midrib confers increased rumen digestibility, green fodder and stover from brown midrib crop cultivars would serve as excellent source of animal feed. Hence, it is worth making research investments on developing high biomass yielding *brown midrib* sorghum, sudan grass, maize and pearl millet hybrids, which besides providing cheaper source for bio-fuel production, meet fodder needs of subsistence farmers. ICRISAT research efforts in breeding *brown midrib* sorghum hybrid parents are yielding positive results (Table 10).

Table 10 Characteristics of selected sorghum brown midrib lines in the 2002 rainy season at ICRISAT, Patancheru, India

Midrib color[a]	Soluble solids (^{0}Bx) at grain maturity (%)	Green fodder yield (Mg ha^{-1})
White grain B-lines		
1.5	13.8	20.8
1.0	14.3	15.2
1.5	17.3	19.0
1.5	20.3	27.4
1.0	17.5	15.3
1.5	15.5	24.5
1.5	22.9	26.9
1.5	13.8	23.7
1.5	18.0	34.6
1.5	17.0	15.1
Red grain cultivars		
1.5	17.3	17.6
1.5	22.0	34.4

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

North American Wild Grass Switch grass (*Panicum virgatum* L.), a perennial grass native to the North American prairies is one of the most sought after grasses for cellulosic bioenergy production. Switch grass planted on large plots (3–9 ha) on marginal crop land on 10 farms across a wide precipitation and temperature gradient in the US mid-continent yielded annual average biomass yield of 5.2–11.1 Mg ha^{-1} with a resulting average estimated net energy yield (NEY) of 60 Gj ha^{-1} year^{-1}. Switch grass produced 540% more renewable than non renewable energy consumed. Estimated average GHG emissions from cellulosic ethanol derived from switch grass were 94% lower than estimated GHG from gasoline. Improved genomics and agronomics may further enhance energy sustainability and bio-fuel yield of switch grass [23]. Switch grass can grow on lands incapable of supporting traditional food crops, with one eighth the nitrogen runoff and 1/100th the soil erosion of conventional crops [16]. Its deep root system adds organic matter to the soil, rather than depleting it. According to the USA Department of Energy, the switch grass yields biomass of about 40 t ha^{-1} and breeding programs should aim at doubling this yield. Expected ethanol output from switch grass biomass is about 450 l t^{-1}.

European Grasses The *Miscanthus* genus (including giant Chinese grass, silver grass, silver banner grass, maiden grass, and eulalia grass) is receiving attention as a potential source of biomass for bio-fuels production. Giant *Miscanthus* (*Miscanthus* × *Giganteus*) is a hybrid grass that can grow four meters tall offer an abundant and inexpensive source of fermentable sugars [27]. Given its rapid growth, low mineral content, and high biomass yield, some European farmers use *Miscanthus* to produce energy [16].

Considering high biomass potential of North American Switch grass and European grasses, it is worthwhile introducing them to China, India and other countries with similar environments. However it is imperative to study the invasiveness of these crops before introducing in new areas.

Table 11 Chemical composition of neem and jatropha seed oil cakes

Chemical	Neem[a]	Jatropha[b]
Azadirachtin	800–900 ppm	–
Nitrogen	4.0 g kg^{-1}	5.7–6.5 g kg^{-1}
Phosphorus	3.0 g kg^{-1}	2.6–3.1 g kg^{-1}
Potassium	1.67 g kg^{-1}	0.9–1.0 g kg^{-1}
Carbon	1.2 g kg^{-1}	–
Sulfur	1.2 g kg^{-1}	–
Calcium	0.77 g kg^{-1}	0.6–0.7 g kg^{-1}
Magnesium	0.75 g kg^{-1}	–

[a] Adilabad, Andhra Pradesh, India
[b] Tumkur, Karnataka, India

Research efforts should be made to evaluate these grasses to identify the agro-ecological regions best suited for their cultivation and to develop and standardize region-specific crop production technologies to maximize biomass production. Also, these grasses need to be genetically improved further for biomass yield and alter cellulose and lignin composition for cheaper production of ethanol.

Bio-Diesel

The non-edible oilseed crops such as jatropha (*Jatropha curcus*), pongamia (*Pongamia pinnata*) and neem (*Azadirachta indica*) are attractive sources of bio-diesel production. Though jatropha is an exotic species (Latin American origin), it is commonly grown in India and other developing countries as hedge and wild bush, whereas pongamia and neem are native to India. These crops were once hallmark of village life, can be grown on lands not suitable for food crops cultivation. For example, pongamia plants are grown in forests as well as avenue plantations in India. These crops are easy to establish, quick growing and hardy, and are not browsed by cattle and goats, and thus making them the best candidates for rehabilitating degraded common lands without any protection. Pongamia being a nitrogen fixer also helps build the soil fertility [30]. Oilcakes, the byproducts after extraction of oil from jatropha and neem are rich sources of macro- and micronutrients (Table 11), and thus serve as an excellent organic fertilizer (Table 12) [30].

Pongamia oil cake in addition is also a proven nitrification inhibitor in fields enhancing nitrogen-use efficiency by reducing nitrate losses. Jatropha oilcake contains about 61% protein compared to about 45% in soybean oilcake [11]. However, the presence of toxins/anti-nutrient factors such as phorbol esters, trypsin inhibitors, lectins, phytates [24], renders Jatropha oilcake unfit for animal feed. After detoxification, oil cakes could be good sources of feed for milch and drought animals, which are indispensable components of mixed crop-livestock system that prevails in Asia and Africa [11]. The neem oil cake, besides providing nutrients to plants has proven insecticidal property, and thus its use not only empowers farmers to improve soil health, but also provide them an eco-friendly means of protecting their crops that support their livelihoods. Developing technologies to make these oilcakes amenable for multiple uses is a key to attract bio-fuel industries and hence to create large demand for biomass sources.

As jatropha and pongamia are still under crop domestication, research is necessary to develop improved cultivars and crop management technologies to maximize seed and oil yields per unit of water and land area. Altering fatty acid composition of the seed oils of these species is a key to improve bio-diesel productivity. At present a large number of jatropha and pongamia accessions are being collected by various research organizations in India under bio-diesel network programs funded by the Department of Biotechnology and National Oilseeds and Vegetable Oils Development Board. The collections are being characterized for their oil content and fatty acid composition by ICRISAT, The Energy Research Institute (TERI), and other institutions in India. Seed oil content ranges from 28% to 40% in jatropha and pongamia accessions that are being maintained and characterized at ICRISAT [30]. In view of their out-crossing, large variability in seed yield and oil content between individual plants is observed. For example, per plant seed yield of jatropha ranges between 200 g to more than 2 kg [24]. The appropriate kind of planting material (vegetative propagation/tissue culture seedlings) need to be therefore standardized, to ensure the true breeding nature of the best clone to be identified or developed through concerted research efforts.

Table 12 Grain yield response of soybean to the application of pongamia press cake and inorganic fertilizers

Treatment	N applied (kg ha^{-1})	Grain yield (kg ha^{-1})	Percent increase over farmers' practice	Net benefit over farmers' practice (US$ ha^{-1})
Farmers' practice (DAP–100 kg)	16	900	–	–
Pongamia press cake (300 kg)	12	1,340	49	106
Fertilizer (urea—50 kg)	23	1,450	61	170
Pongamia cake (150 kg) + urea (25 kg)	17	1,650	83	199

Role of Biotechnology

The genetic improvement of crop plants and tree species offers tremendous potential for making the production of ethanol from lignocellulosic biomass an economic success. Among crop species, sorghum and to some extent corn are likely to play a significant role in enhancing Bio-fuel economies of several communities in the foreseeable future. [28] However, use of corn for bio-fuel depends upon the global food supply and food prices. The advances in biotechnology provide opportunities to significantly reduce cost of bio-fuel production by genetic manipulation of feedstocks in a way that improves bio-fuel yields. The development of genetically engineered sweet sorghums with enriched stalk juice and sugar yields and altered proportion of reducing and non-reducing sugars (in favor of reducing sugars) and efficient microbial fermentors of sugars into ethanol would significantly reduce cost of ethanol production. Similarly, the development of genetically engineered enzymes that can perform both starch hydrolysis and saccharification of cassava root tuber starch, will greatly reduce the cost of conversion of starch into ethanol. Reducing lignin in crop biomass without reduction in biomass yield will substantially improve bio-refinery efficiency. Genomics, proteomics, and metabolomics are being used to improve our understanding of and ability to manipulate the lignin biosynthesis pathway [16]. Care must be however taken, as changes in lignin properties may reduce biomass yield and resistance to pest, disease and lodging and/or alter stover nutritional value [17]. Biotechnological tools hold promise for altering fatty acid composition (intractable trait for manipulation through conventional tools), one of the key traits for improving productivity of bio-diesel from jatropha and pongamia seed oils. Also, addressing more complex traits such as reducing toxins/anti-nutrients in jatropha oilseed cake for making it more valuable as animal feed, requires the use of plant breeding or biotechnology. The success stories on the use of molecular marker-assisted selection to improve the equally complex characteristic of oil concentration in maize kernels or fatty acid composition of soybean oils provide optimism for potential of biotechnological tools to improve crop traits important for bio-fuel production.

Institutional Arrangements for Bio-Fuel Research

Bio-fuel production poses a major new challenge to crop improvement and management research. For farmers to respond to market changes, they need multipurpose crops combining food, feed, fodder, fiber, and bio-fuel traits. Basic research on bio-fuel crops may best be undertaken by upstream academic organizations and the private sector. On the other hand, trait-based mining of genetic resources may be the most appropriate niche for public research organizations, particularly those of international agricultural research centers (IARC) supported by the Consultative Group on International Agricultural Research (CGIAR) [16]. The collaboration with NARS partners is very critical in this endeavor, particularly for strengthening the adaptation research. Clearly there are substantial financial incentives for private investment in developing new crop cultivars for bio-fuel production [2]. Therefore, the breeding of new crop cultivars for the bio-fuel market and development of new microbial/enzyme technologies provide an opportunity for a whole new paradigm in public-private partnerships for bio-fuel research and development. IARC may focus on genetic enhancement of plant genetic resources and feed to national public and private research and extension programs (NARES) worldwide. They may also serve as conduits of new knowledge and technology to small-scale farmers, particularly in resource-poor farming areas of the developing world [16]. These IARC together with national agricultural research systems (NARS) have clear roles in finding suitable mechanisms to ensure that smallholder farmers (particularly those in resource-poor areas) can have sustainable benefits from this potentially lucrative bio-fuel market. Small-holder farmers need to be organized in to groups and linked to input agencies, institutional credit providers and markets to take real advantage of Bio-fuel opportunities. This enhances not only the crop productivity but provide assured market for the produce and better bargaining power to farmers.

Summary

Investments in research and development, and input, credit and market linkages and policy support for Bio-fuel crops production offers opportunities to smallholder farmers to diversify their livelihood options to augment their income levels. Improving the energy value traits of widely cultivated food crops and identifying and genetic enhancement of water-saving non-food/new bio-fuel crops through research is necessary to mitigate trade-offs between food/fodder and energy security. Innovations in existing conversion technologies and/or development of new conversion technologies for efficient production of bio-fuels and the development of technologies that enable efficient use of byproducts in bio-fuel production chain are critical to attract investment in bio-fuels research and commercialization. Development of databases on net energy balance and CO_2 balance of bio-fuel crops are vital to justify increased investments on research and development and commercialization of bio-fuels that have great potential in contributing to energy security of nations.

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