Sorghum as an Energy Source

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The use of sweet sorghum for energy production, principally ethanol production, is discussed. An example of an integrated food, feed, energy, and biofertilizer system is presented. As sorghum is one of the most efficient plants in terms of photosynthesis and as sorghum directly produces fermentable sugars as well as grain, it is one of the most ideal crops for the simultaneous production of energy and food. The industrial by-products can be used as feed, biofertilizer, fiber, and energy. Technology for ethanol production adapted from the sugarcane industry can be utilized almost directly to produce ethanol from sweet sorghum. The additional adaptation of this technology for use in a microdistillery allows for economical small-unit production in a decentralized industry. Transportation costs are reduced and the alcohol is generally consumed by the producer. The process can be completely mechanized or not, depending upon the need to generate jobs and the cost of labor. Production levels have been considered and research recommendations for this decade have been made.

Energy Crisis

Since 1973 when the petroleum cartel OPEC, initiated a series of price increases and more recently with mounting political instability among several OPEC members, much emphasis has been placed on alternate and renewable energy resources and energy independence. Energy prices have increased considerably and energy, principally liquid fuels, has been rationed or considerably taxed to reduce their use in nearly all the petroleum importing nations. This has modified the economies of nearly all the nations of the world and has increased food costs in general, and frequently reduced food and feed production, making it more costly and difficult to feed the world's millions, especially the world's hungry.

Biomass

In many parts of the world, especially the developing nations, one alternative to the energy crises is the production of bioenergy from biomass. In the tropical and subtropical areas, and to a lesser extent the temperate areas of the world, an integrated food, feed, biofertilizer, and energy production system using sweet sorghums [*Sorghum bicolor* (L.) Moench] and high energy sorghums (Miller and Creelman 1980) along with other crops appears to be an economical and logical response for adequate food and energy production.

This paper will concentrate on the aspect of sorghum as a renewable resource for liquid fuel or ethanol production and treat to a lesser degree some possible integrated food and energy systems.

Ethanol—A Renewable Energy Resource

Ethanol has been produced by man since early recorded history as a constituent of fermented beverages. Ethanol as a liquid fuel was used in the earliest automobiles. Henry Ford's early automobiles had carburetors that could be adjusted to use either gasoline or alcohol. Since the early 1900s Brazil has used ethanol mixed with gasoline to utilize surplus alcohol from the sugar industry

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International Crops Research Institute for the Semi-Arid Tropics. 1982. Sorghum in the Eighties: Proceedings of the International Symposium on Sorghum, 2–7 Nov 81, Patancheru, A.P., India. Patancheru, A.P. India: ICRISAT.

and during the World Wars ethanol was used in place of gasoline.

The attractions of alcohol for fuel are many. The world's oil reserves are concentrated in just a few countries, while the potential for producing alcohol from energy crops is as widely diffused as agriculture itself. Liquid fuel from biomass is a renewable resource. Alcohol as a fuel is clean-burning when used alone and when mixed with gasoline it acts to increase the octane rating. Energy crops production and alcohol distillation will require more labor than oil production and refining and thus aid unemployment problems and mass migration to the cities. Because of the transportation limitations of sugar crops, distilleries will be decentralized and dispersed throughout the crop production area.

Alcohol fuel has a powerful political appeal to governments and the common motorist. The problem of balance of payments, possible oil supply disruptions, and rising gasoline prices promote political action toward self-sufficiency. In the United States, which has 40% of the world's automobiles and which uses half of all the gasoline consumed in automobiles, political pressures to produce liquid fuels domestically are particularly strong.

National Energy Policies

Among the countries already producing ethanol for fuel, Brazil is the unquestioned leader. Brazil's alcohol fuel program was launched in 1975. The goal to become self-sufficient in automotive fuel by the end of the century has been upgraded to the end of the eighties. Government incentives include financing to help modernize and expand existing alcohol distilleries, to build new distilleries, and to develop agricultural projects to supply them with feedstock. The national alcohol fuel program is based principally on sugarcane, but also emphasizes sweet sorghum and cassava as distillery feedstock. In 1981/82 Brazil will produce approximately 5 billion liters of ethanol and the target is 11.5 billion liters by the end of 1985. In 1981 the Brazilian Government officially approved the extablishment of microdistilleries with a capacity of up to 5000 liters of alcohol/day. The government's goal is to install 5000 microdistilleries by 1985. These microdistilleries, which function most economically using both sugarcane (6 months) and sweet sorghum (4 or 5 months) (Fig. 1) for a total of 10 or 11 months per year, will be scattered throughout Brazil and the alcohol will be consumed in the locality in which it is produced.

The first United States alcohol fuel program came with the enactment of the Energy Act of 1978. This legislation removed the federal gasoline tax of four cents on every gallon of gasohol, provided the alcohol used in the blend was from nonpetroleum sources. Many states have also made gasohol tax exempt which when combined with the federal exemption amounts to a total subsidy of more than $1 per gallon for ethanol used as automotive fuel.

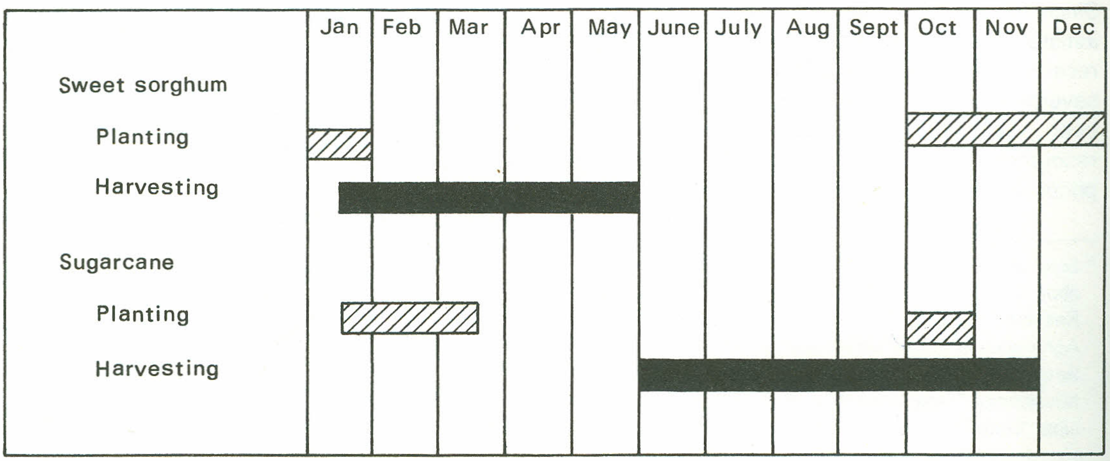


Figure 1. Planting and harvesting periods for sweet sorghum and sugarcane in Brazil (CNPMS/EMBRAPA).

Table 1. United States Department of Energy Projections of annual maximum ethyl alcohol production in the U.S.

Source	1980	1990	2000
	(billions of liters)		
Corn	8.7	3.4	—
Grains, total	14.8	10.6	8.7
Sugarcane	—	2.6	2.6
Sweet sorghum	—	11.4	31.4

Source: U.S. Department of Energy (1979).

Table 2. Alcohol yield of selected crops in the United States and Brazil in 1977.

Crop	Crop yield per hectare (tonnes)	Alcohol yield per hectare (liters)
Sugarcane (Brazil)	54.2	3630
Sweet sorghum (U.S.)	46.5	3554
Corn (U.S.)	5.7	2200
Cassava (Brazil)	11.9	2137
Grain sorghum (U.S.)	3.5	1362
Wheat (U.S.)	2.1	773

Source: Brown (1980).

In January 1980, the federal government announced major new ethanol goals for both 1981 and the mid-eighties. Production of ethanol was to be increased to 1.89 billion liters for fuel in 1981 and 7.57 billion liters by the mid-eighties. Since corn is the primary distillery feedstock in the U.S., this latter goal would expend more than 20 million metric tons of corn.

The U.S. Department of Energy (1979) is considering a major shift from corn to sweet sorghum to produce ethanol (Table 1). For the long-term forecast, it is believed that sweet sorghum could become the dominant energy crop in the United States. A total of 5.67 million hectares of cropland could be planted to sweet sorghum, which would yield 31.4 billion liters of ethanol per year. This cropland would be primarily in the Midwestern and the Southeastern United States.

Many other countries are developing national alcohol fuel programs to reduce their balance-of-payment deficits. Table 2 shows the crop and ethanol yields of selected crops. New Zealand plans to use sugar of fodder beets as the primary distillery feedstock, while Australia and Austria would use wheat. South Africa and the Philippines are planning to use both cassava and sugarcane as raw materials for the production of alcohol. Kenya and Sudan are building alcohol distilleries that will use the molasses by-product of their sugar mills. Thailand plans a flexible agricultural fuel industry that could be adapted to whatever crop might be in greatest surplus. These are but a few of the countries involved in alcohol fuel programs. The future is bright for a crop, such as sorghum, that will produce reasonable yields of alcohol per hectare on marginal lands with minimum production costs. For the present, most countries will use surplus crops or divert some current crop production to alcohol fuel programs. Future programs will bring idle or new marginal lands into the production of sugar crops.

Sweet Sorghum—A Renewable Bioenergy Resource

Types and Composition of Sweet Sorghum

Sweet sorghum grows in a wide geographical range. It can be considered the sugarcane of the temperate zone and it also has a production capacity equal or superior to sugarcane in the tropics when considered on a monthly basis. Two types of sweet sorghum have been developed by breeders: syrup varieties which contain enough invert sugars in the juice to prevent crystallization, and sugar varieties which contain mostly sucrose and very little invert sugars in the juice for crystallization. Estimated approximate compositions of sweet sorghums grown in the United States are shown in Figures 2 and 3 for sugar and syrup varieties, respectively. Sugar varieties have 50% fermentable solids and 30% combustible organics while syrup varieties, on the other hand, have 43% fermentable solids and 33% combustible organics. Total biomass yield of syrup varieties is about 30% more than that of sugar varieties; however, the total soluble solids content of sugar varieties is greater. This difference in production and composition may be due to the narrow genetic base of varieties evaluated, as the number of sugar varieties available is much fewer than the number of syrup varieties. Both types of sweet

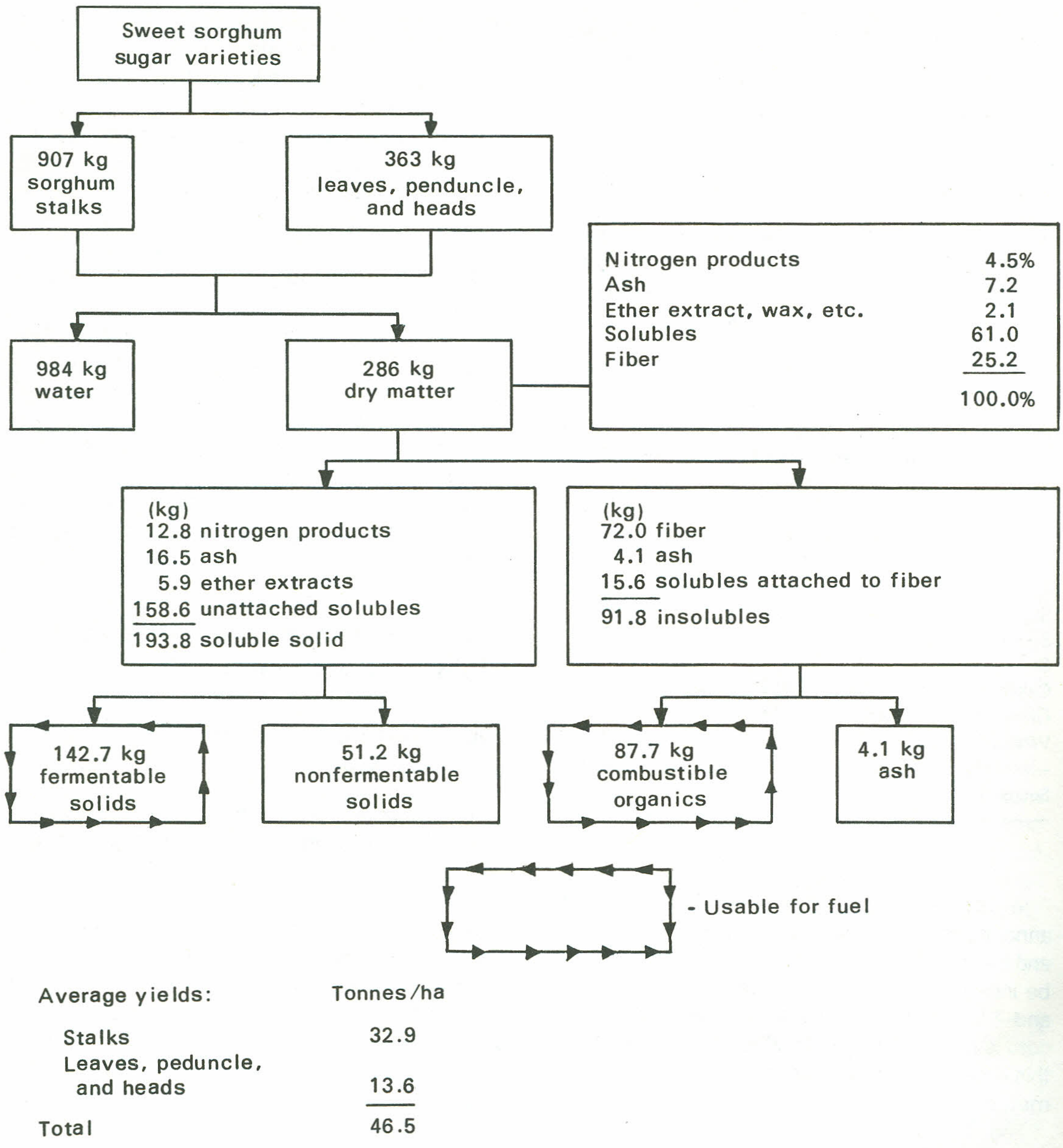
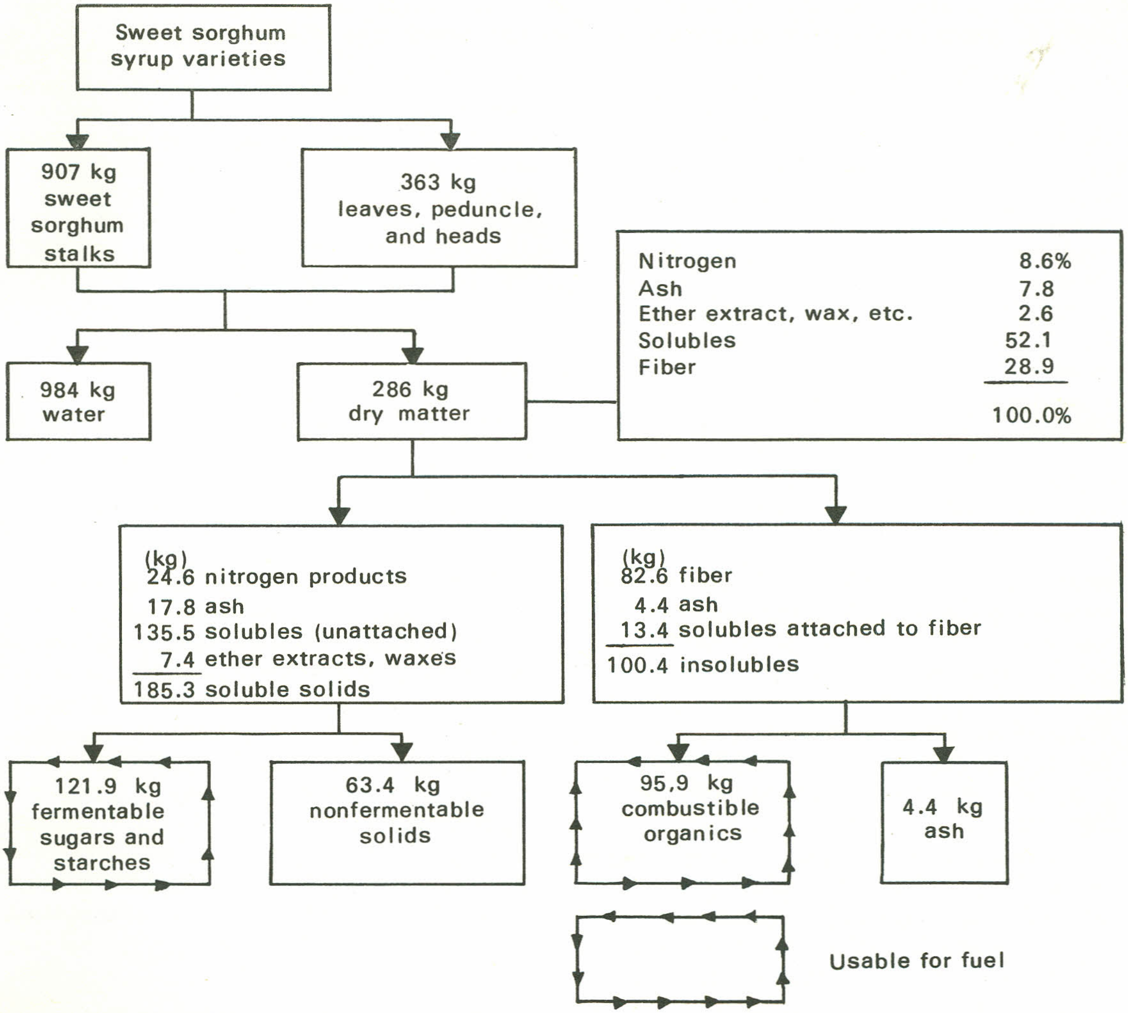


Figure 2. Estimated approximate composition of sweet sorghum sugar varieties in the United States (Nathan 1978).

sorghum are equally suitable for alcohol production as both sucrose and invert sugars are directly fermentable.

Advantages of Sorghum Biomass

Sweet sorghum holds a great potential as a field crop for ethanol production throughout the world because it is adaptable to a wide range of growing conditions, unlike sugarcane which can only be grown in tropical and subtropical climates. Sweet sorghum also has a potential for low unit costs because it requires less water and fertilizer than does sugarcane. More energy will be recovered in the ethanol produced than is used to grow and process the crop, that is, it has a net energy ratio



Average yields:	Tonnes/ha
Stalks	47.4
Leaves, peduncle, and heads	19.3
Total	66.7

Figure 3. Estimated approximate composition of sweet sorghum syrup varieties in the United States (Nathan 1978).

that exceeds 1.0 (Sheehan et al. 1978).

The desirable characteristics of sweet sorghum varieties for ethanol production are: (1) production of a high biomass yield; (2) high percentage of fermentable sugars along with combustible organics; (3) comparatively short growth period; (4) tolerance to drought stress; (5) relatively low fertilizer requirements; (6) production of grain for food or feed use; and (7) the possibility of complete mechanization.

Sorghum—A C_4 Pathway Plant

Sweet sorghum is classified as a C_4 malate-former

Table 3. Maximum dry matter production and maximum growth rates of several crops.

Crop	Dry matter production (t/ha)	Maturity (days)	Average growth rate (gm/m² per day)	Maximum growth rate (gm/m² per day)
Napier.	106	365	26	—
Sugarcane	70	365	18	38
Sugarbeet	47	300	14	31
Forage sorghum	30	120	22	—
Forage sorghum	43	210	19	—
Sudangrass	33	160	18	51
Alfafa	36	250	13	23
Bermudagrass	35	230	14	20
Alga	44–74	300	15–22	28

Source: Loomis and Williams (1963).

which, along with sugarcane and corn, is known to have the highest rate of photosynthesis among crop plants. The C_4 pathway of CO_2 fixation is an auxiliary channel of the primary Calvin-Benson pathway (Hatch 1976). Under natural conditions, C_4 plants are not light-saturated, have CO_2 compensation points near zero, lack detectable photorespiration, and have an optimum temperature of 30–35°C.

One of the most important features of C_4 plants is their specialized leaf anatomy (Krantz-type) which provides the spatial compartmentalization required to absorb and fix low concentrations of atmospheric CO_2 in two separate sets of reactions. Atmospheric CO_2 is fixed by the C_4 pathway only in the leaf mesophyll cells while the Calvin-Benson cycle fixes CO_2 predominantly in the leaf bundle sheath cells. The net effect in C_4 plants is that they exhibit a very high photosynthetic capacity which is about twice as great as that of C_3 plants. Any CO_2 produced by photorespiration must diffuse out through bundle sheath cells and then through the actively fixing, but nonphotorespiring, mesophyll tissue before it could escape into the atmosphere and be detected by existing methods of measuring photorespiration. This of course leads to greater efficiency in utilizing CO_2.

Photosynthetic Efficiency

The data of Loomis and Williams (1963) in Table 3 show that sorghum has one of the highest dry matter accumulation rates when considered on a daily basis. In terms of average growth rate, sorghum is exceeded only by napier grass. In the data presented by Heichel (1976), sorghum had the highest food energy per unit cultural energy ratio, exceeding corn silage, sugarcane and corn grain. Considering these results, sorghum appears to be one of the most photosynthetic efficient genera that can be produced in both temperate and tropical environments, completely mechanized, and utilized on a large scale with existing technology for energy production. Undoubtedly, as more attention is placed on bioenergy production in the future, more attention will also be given to sorghum.

Technology and Infrastructure for Producing Ethanol from Sorghum

Ethanol from sweet sorghum has been produced in pilot runs in several large-scale commercial sugarcane distilleries of 120 000 liters per day or larger capacity, and is currently being produced commercially in several microdistilleries of 2000–5000 liters per day capacity, in Brazil. In both cases the flow diagram is similar, and two processes for microdistilleries will be considered here. The differences between microdistilleries and distilleries of large-scale capacity are: the number of units of roller mills, the efficiency of extracting sugars, and the efficiency of fermentation and distillation.

In Brazil, the normal harvesting period for sugarcane is from June to November and the harvesting period for sweet sorghum is from February to May with plantings beginning in

October and November (Fig 1). In this case, the two crops supplement one another and when used together increase the period of industrial operation, decrease the unit cost of alcohol production, and increase the total amount of alcohol that can be produced by a distillery in one year. The same equipment is used to process both sugarcane stalks and sweet sorghum stalks. Consequently, little interest is given to the superior productivity of sugarcane or sweet sorghum but rather an economic production of both sugarcane and sweet sorghum.

Sugar Extraction Using Roller Mills

A simple flow diagram of a microdistillery using roller mills for sugar extraction is shown in Figure 4. The stalks of either sweet sorghum or sugarcane are crushed in the roller mills and the sugars extracted with the juice. The efficiency of juice and sugar extraction depends upon the pressure of the rollers and the number of units. When two or more units are used, the efficiency can be improved by using a small amount of hot water for imbibition. The efficiency also depends upon the nature of the stalk and this will be discussed in the section on plant breeding and improvement. The untreated juice is mixed with yeast and minerals, and is fermented. After the sugars have been transformed to alcohol, the beer is distilled to 92% ethanol for direct use in motors or to 100% ethanol to mix with gasoline. The bagasse can be burned in the boiler to produce steam or can be used for feed, fiber, or as a cellulose feedstock for other processes. The stillage can be used as a biofertilizer and returned to the soil or used as a feedstock in a biodigestor to produce methane and biofertilizer.

Sugar Extraction by Diffusion

A simple flow diagram of a microdistillary using a simple horizontal diffusor for sugar extraction is shown in Figure 5. The major difference in these two processes is the use of hot water to extract the sugar from the stalks in the diffusor. A roller

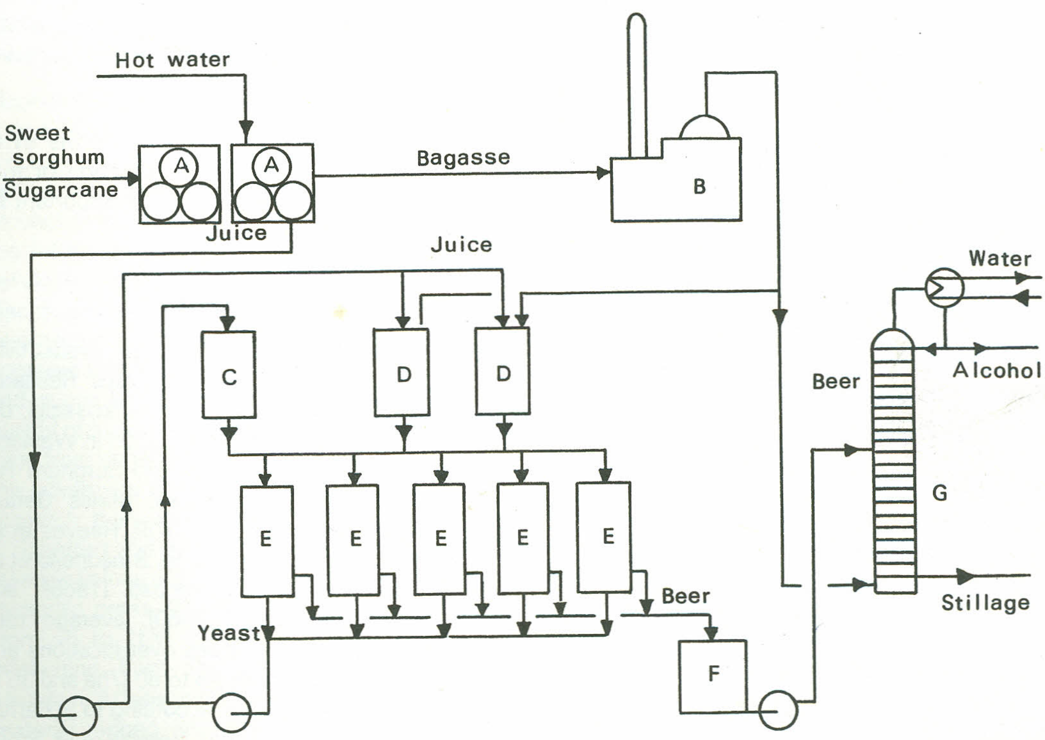


Figure 4. A simple flow diagram of a roller mill microdistillery. A—roller mill, B—boiler, C—yeast treatment and distribution tank, D—juice distribution tanks, E—fermentation tanks, F—beer-holding tank, and G—distillation column (CNPMS/EMBRAPA).

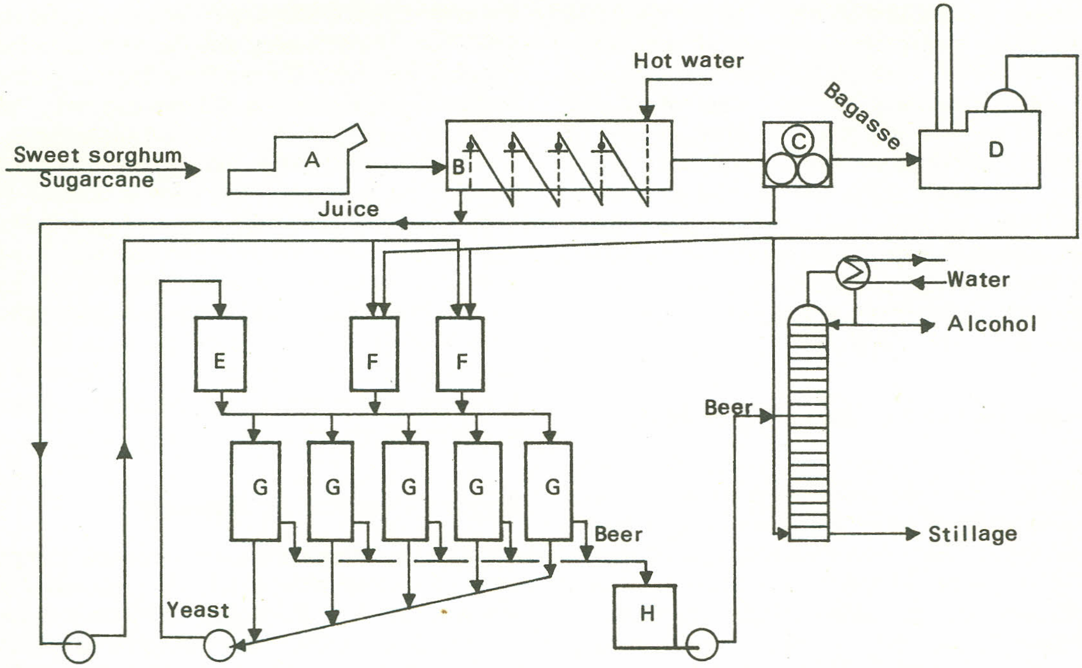


Figure 5. A simple flow diagram of a diffusion microdistillery. A—forage chopper, B—diffusor, C—roller mill, D—boiler, E—yeast treatment and distribution tanks, F—juice distribution tanks, G—fermentation tanks, H—beer-holding tanks, and I—distillation column (CNPMS/EMBRAPA).

mill is still necessary for removing the residual juice from the bagasse. An additional roller mill may also be placed before the diffusor for greater efficiency of sugar extraction. The efficiency of sugar extraction in this process is generally greater than 90% and equivalent to large-scale sugarcane distilleries.

Sweet Sorghum Productivity and Quality

Sweet sorghums or sorgos for syrup production have been produced in the USA for over 100 years whereas the technology to produce sugar (sucrose) from sweet sorghum on a commercial scale has been available for only the past 10 to 15 years. Research on alcohol production using sweet sorghum is even more recent and for the most part has been conducted during the last 5 years. Both types of sweet sorghum serve to produce alcohol but good types to produce alcohol do not need to be associated with high sucrose purity of the sugar types or the quantity and quality of syrup produced per ton of stalks of the syrup types. The total amount and extraction of total invert sugars (fermentable sugar) is important for alcohol production.

Sweet Sorghum Productivity

The most complete sweet sorghum productivity data are from the U.S. Sugar Crops Research Station of the USDA at Meridian, Mississippi, the Texas Agricultural Experiment Station at Weslaco, Texas and the National Corn and Sorghum Research Center at Sete Lagoas, Minas Gerais, Brazil. According to Reeves (1976), Reeves et al. (1978), Reeves and Smith (1979), Broadhead et al. (1974), Coleman and Broadhead (1968), and Schaffert and Borgonovi (1980), average total yields of commercial varieties over locations and years normally range from 45 to 60 t/ha and 35 to 48 t/ha for stripped stalks. According to Schaffert and Borgonovi (1980a) and Reeves and Smith (1979) experimental breeding lines and progenies have been more productive, with yields ranging from 80 to 100 t/ha of sorghum (total plant).

Table 4. Comparison of juice quality between sweet sorghum and sugarcane in Brazil.

Trait	Sweet sorghum		Sugarcane (São Paulo State averages)
	Literature	National trials	
Juice extraction (%)	350–600	500–700	600–800
Retractometer Brix	16–20	14–20	18–21
Sucrose (% juice)	10–15	8–16	15–18
Invert sugars (% juice)	1–4	0,7–7,3	0,2–1,5
Total invert sugars (% juice)	14–20	14–18	16–19

Source: Schaffert and Borgonovi (1980b).

These yields have been with maturity types ranging between 110 and 140 days. Reeves and Smith (1979) have reported yields surpassing 100 t/ha fresh weight with longer maturity types. Under optimum large-scale field operations, Schaffert and Borgonovi (1980b) have reported total fresh weight yields exceeding 80 t/ha with 130 to 140 day maturity types. Grain yields normally range between 1.5 and 5.5 t/ha with average yields between 2 and 3 t/ha.

Sweet Sorghum Quality

Alcohol from sweet sorghum is currently produced with technology and equipment used to process sugarcane and during the next few years will probably continue to be processed this way. Alcohol or liquid fuel production from biomass in the future may include technology to utilize the cellulose fraction directly in the process. The discussion here will be primarily limited to the parameters dealing with ethanol production using sugarcane technology. In Table 4, sweet sorghum and sugarcane juice quality are compared. The quality of juice from sorghum is slightly inferior to juice from sugarcane, but then sugarcane has had the advantage of a substantially longer period of research than sorghum.

Schaffert and Borgonovi (1980b) have obtained average values of juice extraction (Table 5) using a hydraulic press (250 kg/cm² for 60 sec) ranging from 45 to 76% in a collection of 55 varieties originating from the germplasm collection at Meridian, Mississippi. Percent fiber in the same material ranged from 10 to 27%. The values of Brix and total invert sugars were relatively low as the material was sampled within a short span of time and at different stages of maturity. The variety Wray appears to be one of the most promising varieties for both commercial use and in a breeding program. Figures 6–9 demonstrate the interrelationship between the curves of refractometry Brix of the juice, total invert sugars in the juice extraction, fiber, and total invert sugar extraction for the varieties Wray, Rio, Brandes, and CMSTx 623, respectively. In Figures 10–13 the differences between these four cultivars, grown in Brazil, for refractometry Brix, total invert sugars in the juice, juice extraction, fiber, and total invert sugar extraction are shown. In Figure 13, the period for industrial utilization (PIU) for Wray is much superior to Rio and slightly superior to Brandes and CMSTx623. PIU is the period of time that total invert sugar extraction of a cultivar is the greatest and at an economical level. Wray generally has an acceptable PIU exceeding 40 days, whereas Rio generally has an acceptable period of less than 20 days. This difference is not due to the quantity of total invert sugars in the juice, but rather to differences in juice extraction and percent fiber (Fig. 12). Wray is a superior variety for both the stalk crushing and the diffusor process of sugar extraction. The varieties Brandes and CMSTx 623 also have values more desirable than Rio. Reeves and Smith (1979) have obtained between 2 and 4% starch in dry stalks of sorghum. Smith (personal communication, USDA, Texas Agriculture Experiment Station, Weslaco, Texas, 1978) has reported similar values of starch in the juice extracted from stalks. This starch does not interfere in the fermentation and distillation process but could be hydrolized and converted to simple sugars before fermentation. Figure 14 demonstrates the major potential uses of sweet sorghum for food, fiber, fertilizer, ethanol and methane gas production. The only phase untested

Table 5. Average values of Brix, total invert sugars, juice extraction, and fiber of selected sweet sorghum varieties grown at Araras, São Paulo, Brazil in 1981.

Variety	Brix	Total invert sugars (% juice)	Extraction (% sorghum stalk)	Fiber (% sorghum stalk)
Brandes	16.7	14.7	63.2	12.5
Honey	13.0	11.1	73.0	11.6
Sart	14.7	12.4	69.8	14.8
Rio	16.4	14.2	57.6	16.1
MN 1500	14.2	11.4	61.1	18.5
MN 1048	14.1	13.4	56.5	22.0
MN 1030	15.2	10.0	47.6	25.8
MN 4008	10.6	10.5	74.9	12.0
Williams	13.5	12.4	70.5	10.1
MN 4080	14.1	—	45.7	26.6
Wray	19.3	16.8	67.5	14.8
Theis	16.4	14.2	71.5	14.8
Redlan	10.5	7.4	67.0	13.6
Tx623	10.8	7.0	64.0	13.6

Source: Schaffert and Borgonovi (1980b).

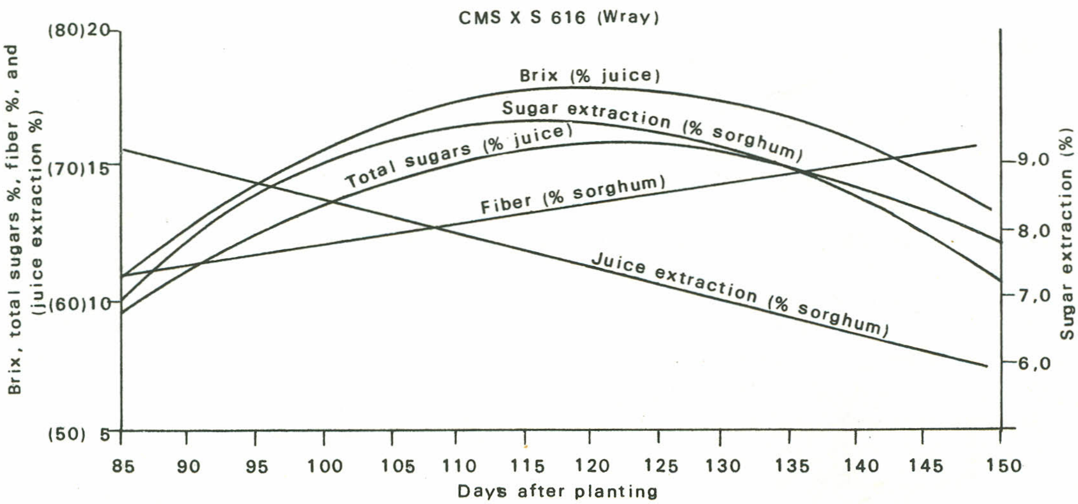


Figure 6. The interaction of refractometry Brix and percent total invert sugars in the juice and percent fiber, percent juice extraction, and percent sugar extraction of sorghum stalks during the maturity phase for the variety Wray grown in Brazil (CNPMS/EMBRAPA).

at the National Corn and Sorghum Research Center in Brazil is the hydrolysis of the bagasse. In the case where this system is integrated with a greenhouse system, the CO_2 from the fermentation could be used to increase the CO_2 concentration in the greenhouse. The biofertilizer can also be used in a greenhouse system. Figure 15 demonstrates an integrated rural energy system developed at the National Corn and Sorghum Research Center in Brazil that can operate on a

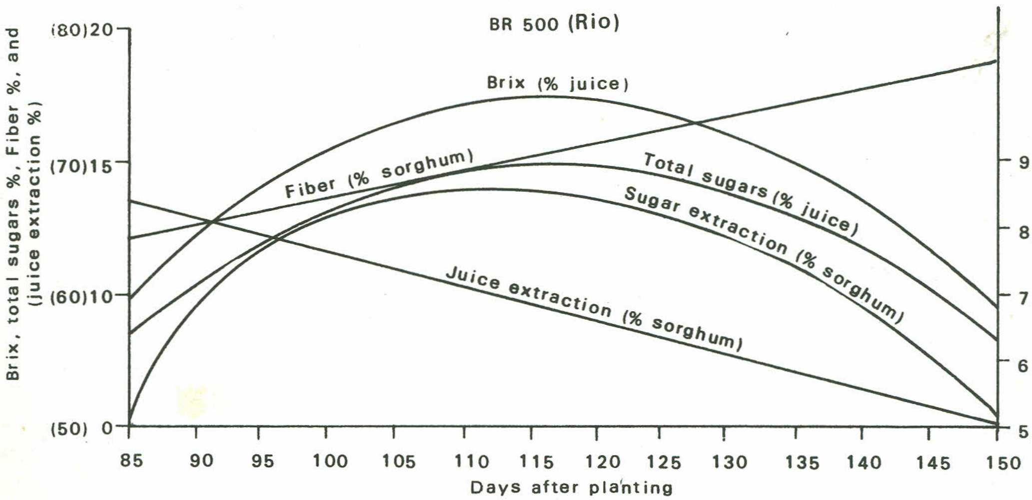


Figure 7. *The interaction of refractometry Brix and percent total invert sugars in the juice and percent fiber, percent juice extraction, and percent sugar extraction of sorghum stalks during the maturity phase for the variety Rio grown in Brazil (CNPMS/EMBRAPA).*

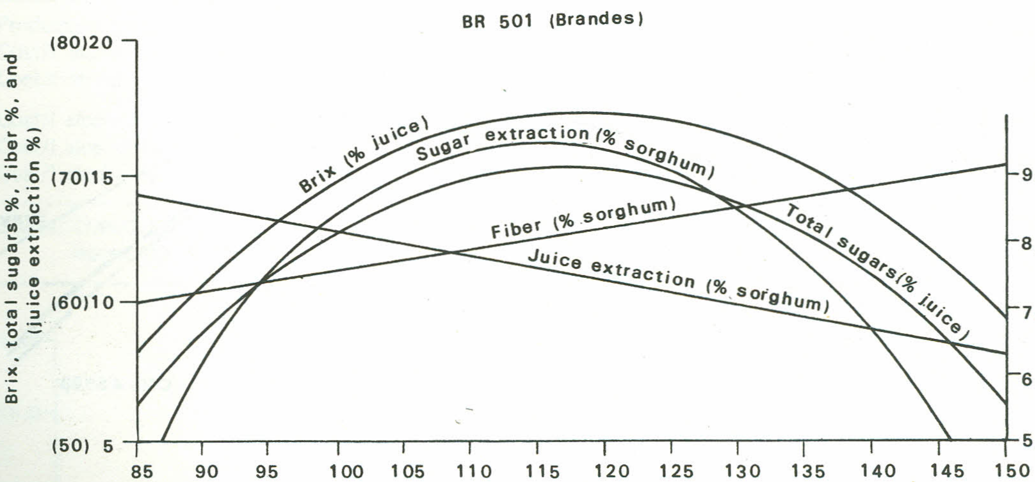


Figure 8. *The interaction of refractometry Brix and percent total invert sugars in the juice and percent fiber, percent juice extraction, and percent sugar extraction of sorghum stalks during the maturity phase for the variety Brandes grown in Brazil (CNPMS/EMBRAPA).*

zero petroleum and electrical energy input basis. Many other options are also possible for total utilization of the sorghum plant.

Economics of Producing Alcohol from Sorghum

Table 6 shows the range and average yields of sweet sorghum and ethanol production used for planning purposes in Brazil. Agricultural yields can be much higher than 37.7 metric tons of stalks and 2.2 metric tons of grain per hectare under good management. The average industrial yields are those obtained by large industrial operations and are currently about 20% less for microdistilleries. Utilizing both the grain and the stalks to produce alcohol, one hectare will produce 3387 liters of ethanol in 4 months. The utilization of one

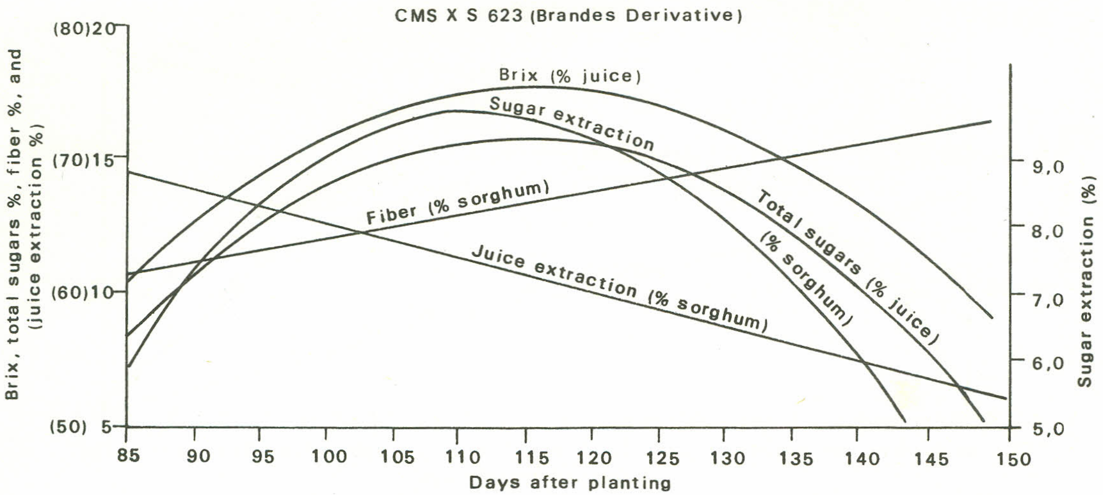


Figure 9. *The interaction of refractometry Brix and percent total invert sugars in the juice and percent fiber, percent juice extraction, and percent sugar extraction of sorghum stalks during the maturity phase for the variety CMSXS 623 grown in Brazil (CNPMS/EMBRAPA).*

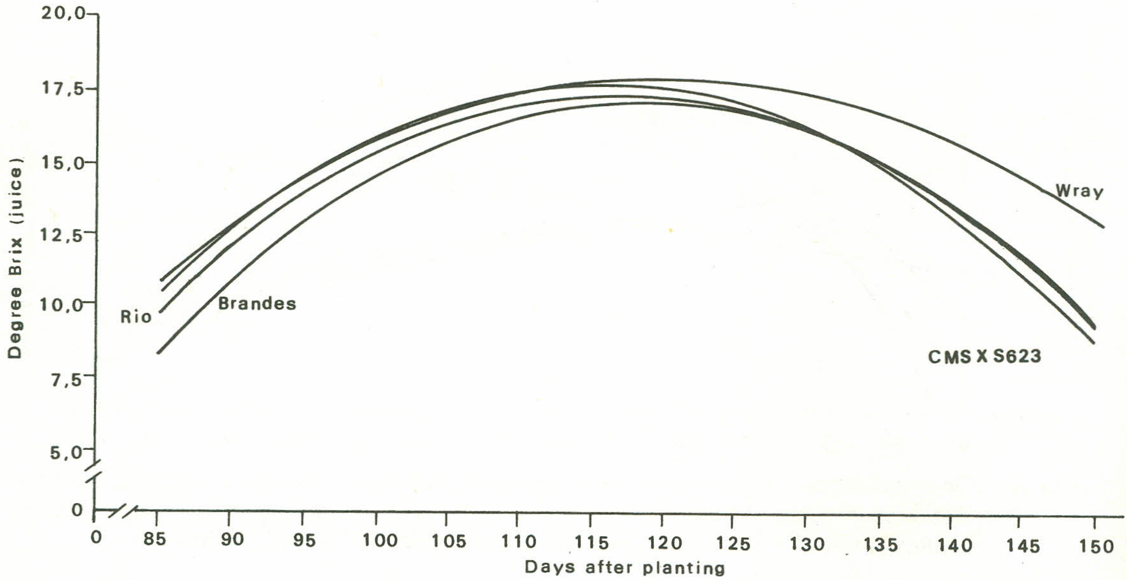


Figure 10. *The differences between four cultivars grown in Brazil for refractometry Brix of the juice during the maturity phase of production (CNPMS/EMBRAPA).*

ratoon crop would increase this value by 50 –80%. Table 7 shows the production costs of ethanol from sweet sorghum stalks in Brazil in November of 1980 considering two levels of stalk production and three industrial production levels representing three types of microdistilleries, one crushing unit, two crushing units and a diffusion unit respectively. Horizontal and vertical diffusion units for microdistilleries are currently being evaluated in Brazil.

Table 6. Agricultural and industrial yields of sweet sorghum in Brazil.

Component		Agricultural yield (t/ha)	Alcohol yield	
			(liter/t)	(liter/ha per harvest)
Stalks	Range	22–66	55–85	1210–5610
	Average	37.7	70	2639
Grain	Range	1.4–6.6	310–370	434–2442
	Average	2.2	340	748
Total	Range			1644–8052
	Average			3387

Source: Schaffert and Borgonovi (1980b).

Table 7. Production costs of alcohol from sweet sorghum in Brazil in microdistilleries, November 1980.

Item	US$
Production costs/ha	320
Cost/t stalks (30 t/ha)	10.67
Cost/t stalks (40 t/ha)	8.00
Cost/l alcohol (45 liter/t and 40 t/ha)	0.22
Cost/l alcohol (59 liter/t and 40 t/ha)	0.20
Cost/l alcohol (68 liter/t and 40 t/ha)	0.17

Source: CNPMS/EMBRAPA, Caixa Postal, 151, 35700-Sete lagoas, MG, Brazil.

Future Sorghum Biomass Research and Development

Development of Improved Cultivars

Insensitivity to Photoperiodism

One of the factors limiting sorghum biomass production in the tropics and subtropics is the sensitivity of most of the cultivars to photoperiodism. This seriously limits varietal management for a prolonged harvest period of several months. Two principal sources for insensitivity used in the Brazilian sweet sorghum improvement program

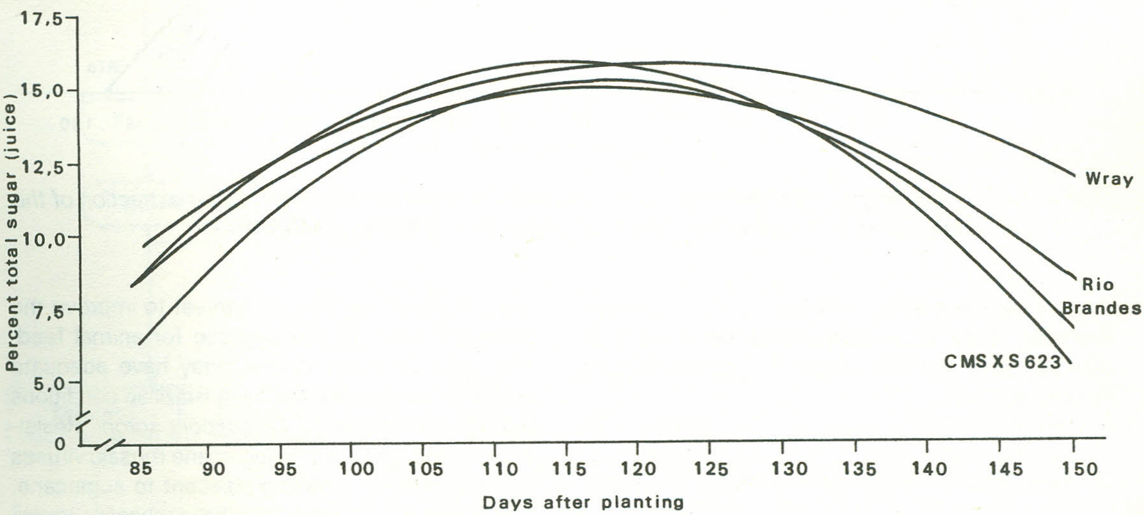


Figure 11. The differences between four cultivars grown in Brazil for total invert sugars of the juice during the maturity phase of production (CNPMS/EMBRAPA).

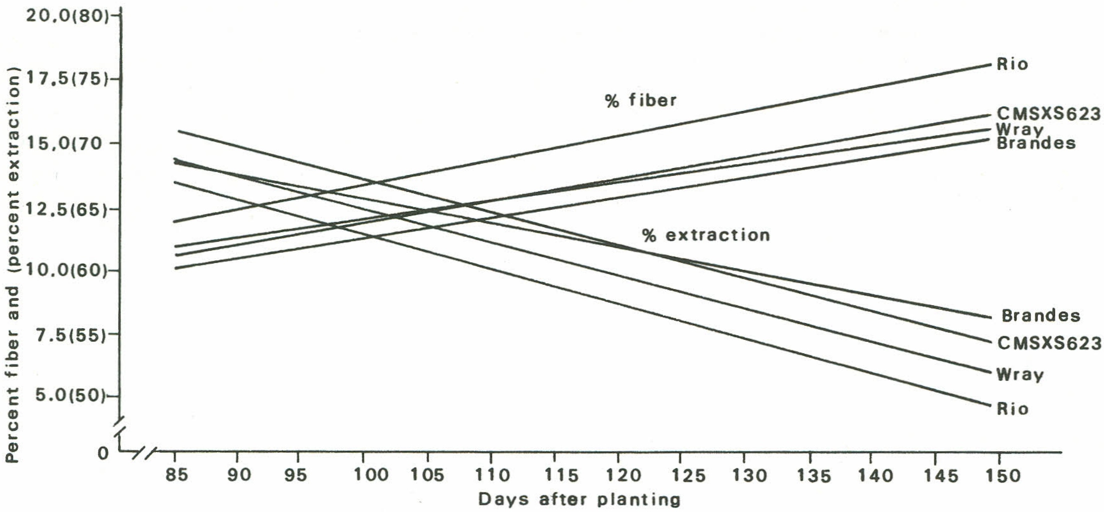


Figure 12. *The differences between four cultivars grown in Brazil for juice extraction and fiber of the stalks during the maturity phase of production (CNPMS/EMBRAPA).*

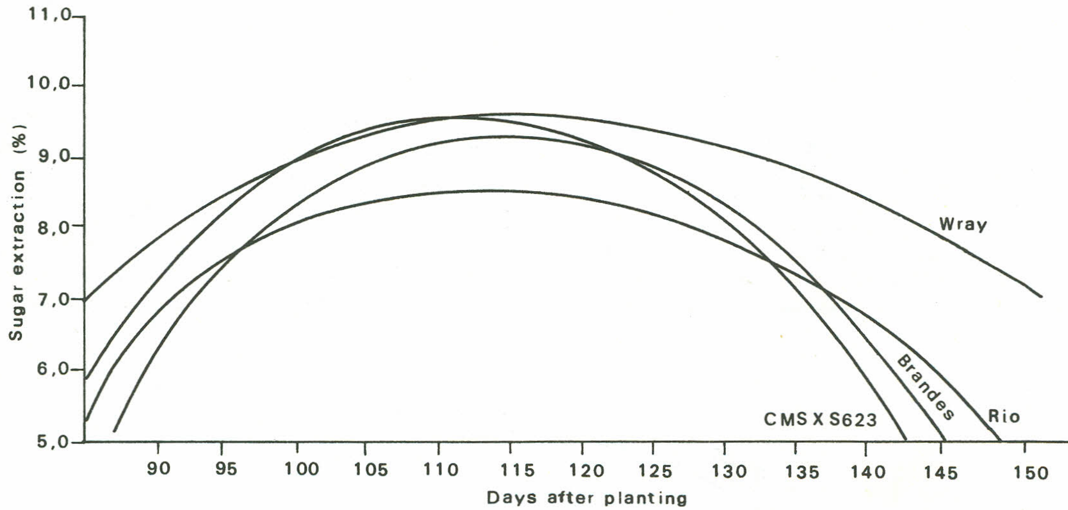


Figure 13. *The differences between four cultivars grown in Brazil for total invert sugar extraction of the stalks during the maturity phase of production (CNPMS/EMBRAPA).*

are the varieties Wray and Honey. The varieties Brandes, Theis, Dale, Roma, and Ramada are all very sensitive and the variety Rio is intermediate in reaction.

Disease and Insect Resistance

Cultivars with good levels of resistance to foliar diseases are needed to maintain a high percentage of green leaves until harvest to improve the biological value of the bagasse for animal feed. The varieties Brandes and Wray have adequate levels of disease resistance in Brazilian conditions but are susceptible to *Cercospora sorghi*. Resistance or immunity to the sugarcane mosaic viruses is necessary for cropping adjacent to sugarcane. Good insect resistance is also necessary, especially resistance to the sugarcane borer (*Diatraea* spp).

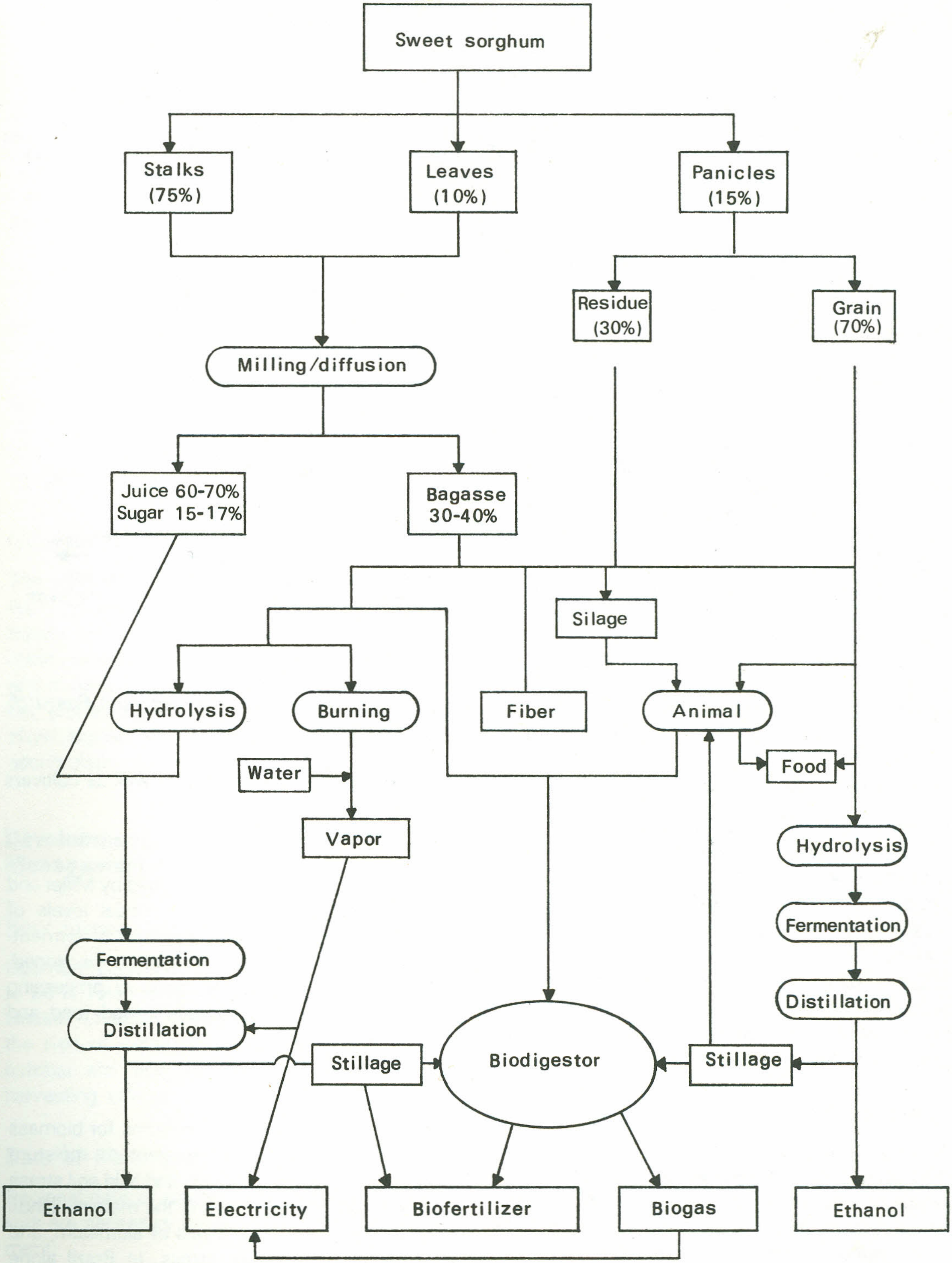


Figure 14. The potential uses of sweet sorghum for food, fiber, fertilizer, ethanol, and methane gas production (CNPMS/EMBRAPA).

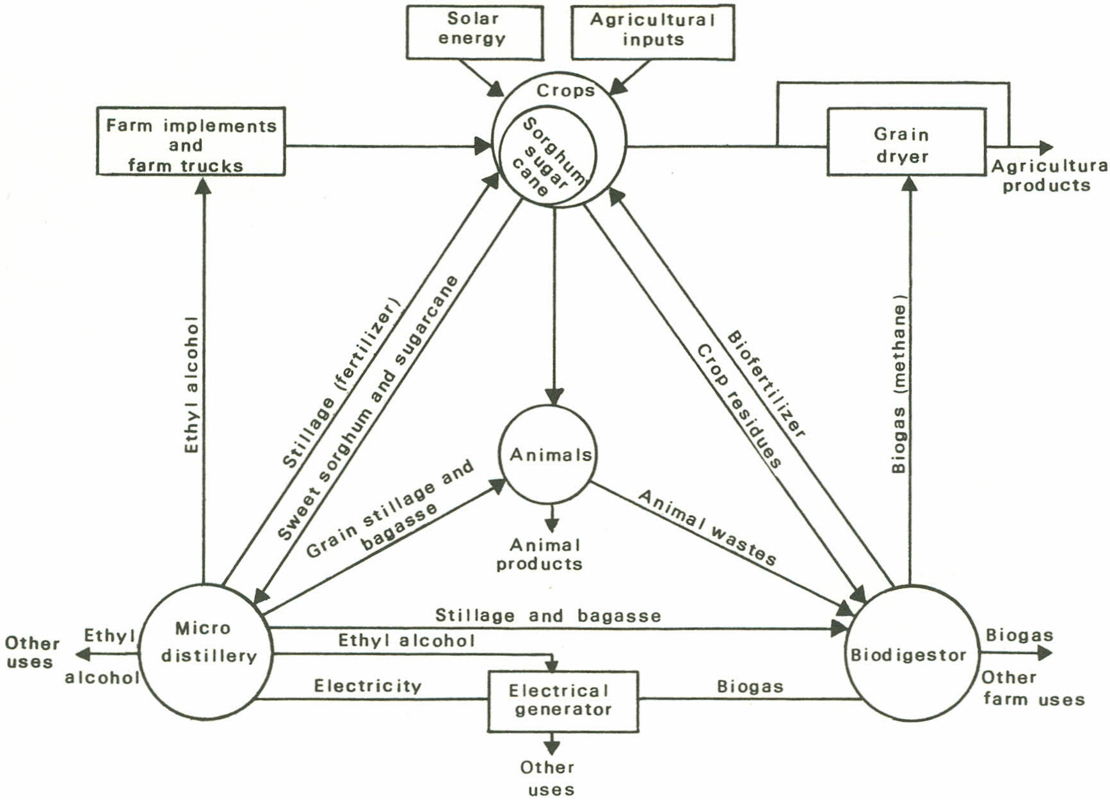


Figure 15. An integrated rural energy system developed at the National Corn and Sorghum Research Center of EMBRAPA in Brazil (CNPMS/EMBRAPA).

Male-sterile Sweet Sorghum Lines

A new series of A and B sweet sorghum lines is needed to produce hybrids. Hybrids produced with the available A-lines are significantly more productive but the juice quality is reduced and the level of total invert sugars is more variable than for commercial cultivars. Lines such as Redlan, Tx 622, Tx 623 and Tx 624 have not produced adequate hybrids. The cost of hybrid seed production is much less than the cost of variety seed production due to harvest costs.

Maturity Groups

New cultivars with varying maturity lengths, 100–210 days, are needed to improve varietal management for a longer total harvest period. Most cultivars produced in the tropics normally reach maturity between 110 and 140 days.

Improved Industrial Quality

Cultivars with greater total sugars, lower fiber, and greater sugar extraction, as well as cultivars with a longer PIU are needed.

High Energy Sorghum

High energy sorghums, as proposed by Miller and Creelman (1980), with high potential levels of grain production and large quantities of fermentable sugars in their stalks should be developed. This will provide a greater range of processing systems that can be employed for food, feed, and energy production.

Stress Tolerance

It is necessary to develop sorghums for biomass production that are more tolerant to moisture stress, toxic aluminum stress, and acid soil stress so that these can be grown in the marginal lands that are acid, with toxic levels of aluminum, and are subject to moisture stress. In Brazil alone there are more than 180 million hectares of land with these characteristics that are not currently in crop production.

Development of Basic Studies

Seedling and Initial Growth Rates

Sweet sorghums are slow starters, they have slower growth rates than grain sorghum for the first 20–30 days of growth. The factors associated with this trait need to be identified to allow breeders to develop fast starters.

Herbicide and Insecticide Resistance

Sweet sorghums are generally much more susceptible to chemical damage than other sorghums and grasses. Sources of resistance need to be identified for utilization in a breeding program. The use of protection agents mixed with the seed to give a greater range of herbicide use is also needed.

Growth Curves

The development of growth curves associated with sugar metabolism and accumulation is needed as well as studies to determine the optimum stalk size for maximum sugar production and maximum sugar extraction during the industrial processing phase. Other biochemical and physiological aspects of sugar production and accumulation also need to be studied.

Development of Improved Management Practices

Row Spacing and Plant Density

Optimum plant spacing and density studies need to be developed to determine the correct combination of total productivity, stalk size, and the the type of industrial processing. Stalk size and number are also important factors in manual harvesting efficiency.

Date of Planting Studies

Regional date of planting trials for adapted cultivars are necessary for optimum varietal management.

Mechanization

The lack of adequate planting equipment necessary for uniform stands is a limiting factor in many of the tropical areas of the world and adequate planting and management systems need to be developed. Systems of mechanized harvest or semimechanized harvest compatible with the industrial process need to be developed.

Weed Control

Adequate weed control systems need to be developed. The use of seed protection agents for greater herbicide choice and combinations of mechanical and chemical control methods need to be developed and improved.

Ratooning

Production systems utilizing one or two ratoon harvests need to be developed. Until recently, with the introduction of photoinsensitive varieties ratoon cropping was not possible in the short-day tropical environments. Schaffert and Borgonovi (1980a) obtained total production of 166 t/ha sorghum in three harvests near Petrolina, Pernambuco, Brazil with a selection from the variety Honey in one year. New cultivars and systems for ratoon cropping are essential for efficient varietial management.

Fertilizer Calibrations

Fertilizer recommendations need to be developed for high yielding sweet sorghums where the entire crop is removed and stillage and biofertilizer may or may not be applied to the soil. Reeves et al. (1978) reported a range of removal of potassium from the soil varying from 132 to 515 kg/ha for three sweet sorghum cultivars. The phosphorus removed was much less and ranged from 15 to 37 kg/ha.

Development of More Efficient Industrial Processes

The most promising system for the immediate future, using sweet sorghum, is the microdistillery with a capacity ranging from 500 to 5000 liters per day. These are small cooperative or large farm systems where approximately 10% of the crop land area is needed for zero petroleum energy inputs and where the by-products can be utilized on the farm. Additional studies of stillage and biofertilizer rates need to be made for optimum utilization of these products. Improving the efficiency of sugar extraction, cellulose hydrolysis (biodigestor), fermentation, distillation and heat transfer is important. Technology for more efficient utilization of ethanol and biogas in farm motors is also desirable. The biological values of the by-products for animal feed also need to be evaluated. Economical methods to utilize the starch in the extracted juice for alcohol production need to be developed for microdistilleries.

Fuel or Food or Fuel and Food

Using energy crops as a source of fuel places a new demand on agriculture to produce an adequate food supply. In the 1980s we will see a much larger quantity of agricultural resources being diverted to the production of nonfood crops than could have been imagined in the 1970s. Food-exporting countries such as the United States, Brazil, Australia, New Zealand, and South Africa are actively pursuing programs for the conversion of crops into alcohol for fuel on a commercial scale. As oil prices increase, distillers will be able to increase the price of ethanol and will become competitive in grain markets. The use of sugar crops for liquid fuel will also compete for the world's cropland to a large extent. The use of sweet sorghum for liquid fuel production does not need to be a question of fuel or food but rather an option of fuel and food.

Conclusion

If the production of large quantities of ethanol for fuel from sugar crops becomes a reality, the future of sweet sorghums in the eighties and beyond indeed looks bright. Sorghum breeders must utilize the tremendous genetic diversity of this genus and direct breeding efforts toward developing improved varieties and hybrids as a crop for fuel and agronomists must develop production systems for the many industrial options available for processing sweet sorghum.

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References

BROADHEAD, D. M., FREEMAN, K. C., COLEMAN, O. H., and ZUMMO, N. 1974. Theis—a new variety of sweet sorghum for syrup production. Mississippi Agricultural and Forestry Experiment Station Information Sheet 1236. Mississippi State, Mississippi, USA: Mississippi State University.

BROWN, L. R. 1980. Food or fuel: new competition for the world's cropland. Worldwatch Paper 35. Washington, D. C., USA: Worldwatch Institute.

COLEMAN, O. H., and BROADHEAD, D. M. 1968. Brandes, a new variety of sweet sorghum for syrup production. Mississippi State University Agriculture Experiment Station Information Sheet 1013. State College, Mississippi, USA; Mississippi State University.

HATCH, M. D. 1976. The C_4 pathway of photosynthesis: mechanism and function. Pages 59–81 *in* CO_2 metabolism and plant productivity, eds. R. H. Burris, and C. C. Black, Baltimore, Maryland, USA: University Park Press.

HEICHEL, G. H. 1976. Agriculture production and energy resources. American Scientist 64 : 64–72.

LOOMIS, R. S., and WILLIAMS, W. A. 1963. Maximum crop productivity: an estimate. Crop Science 3 : 67–71.

MILLER, F. R., and CREELMAN, R. A. 1980. Sorghum—a new fuel. *In* Proceedings, 35th Annual Corn and Sorghum Research Conference, American Seed Trade Association.

NATHAN, R. A. 1978. Fuels from sugar crops: systems study for sugarcane, sweet sorghum, and sugar beets. Oak Ridge, Tennessee, USA: United States Department of Energy, Technical Information Center.

REEVES, S. A. 1976. Sweet sorghum research report, 1975. Technical Report 76–3. College Station, Texas, USA: Texas Agricultural Experiment Station, Texas A&M University.

REEVES, S. A., HIPP, B. W., and SMITH, B. A. 1978. Sweet sorghum biomass—a renewable energy source. Technical Report 78–1. College Station, Texas, USA: Texas

Agricultural Experiment Station, Texas A&M University.

REEVES, S. A., and SMITH, B. A. 1979. Sweet sorghum biomass—a renewable energy source. Part 2. Technical Report 79–1. College Station, Texas, USA: Texas Agricultural Experiment Station, Texas A&M University.

SCHAFFERT, R. E., and BORGONOVI, R. A. 1980a. Sorgo -uma opção para a produção de alimentos e energia. A Granja. 36: 60–64. Editora Centaurus Ltda., Porto Alegre, Brazil.

SCHAFFERT, R. E., and BORGONOVI, R. A. 1980b. Perspectivas de sorgo sacrino para produção de etanol. In press *in* Simpósio sobre alcool. Academia de Ciências do Estado de São Paulo, Brazil.

SHEEHAN, G. C., GREENFIELD, P. F., and NICKLIN, D. J. 1978. Energy economics, ethanol—a literature review. *In* Proceedings, Alcohol Fuels Conference, Sydney, Australia.

USDOE (United States Department of Energy). 1979. The report of the alcohol fuels policy review. Washington, D. C.: U. S. Government Printing Office.