prevent heat loss at night. The possibilities of greenhouse-residences are under review[14].

Solar stills may be a means of providing fresh water for crop production in arid lands. They are semi-cylindrical plastic tunnels or ground mulches positioned over polluted or brackish water or over sandy irrigated soils. They can effect considerable water vapor condensation as well as reduce water losses by evaporation. The opportunity lies in integrated solar still-bubble greenhouse combinations for the production of high value crops[15].

The most extensive use of solar energy collectors for crop production is in the use of plastic covers and soil mulches for promoting early seedling growth and water conservation in temperate zone agriculture. Significant developments are those in China where rice crops from seedlings covered with plastic mature 2-3 weeks earlier. Especially significant results have been obtained with maize in France by mulching with clear plastic. Maturity is advanced by 3-4 weeks and the yields are doubled[16]. Indeed, this is one of the important options for the future enhancement of food production in agriculturally developing as well as for industrialized nations.

In conclusion, a model for future agricultural technology relating to resource inputs would be that which is scale neutral, non-polluting and environmentally benign, which would add to the resources of the earth, result in stable production at high levels, be sparing of capital, management and resources, and which could be alternatively labor intensive or labor saving. Future developments in the use of solar energy for the production and processing of agricultural products should well satisfy the above criteria.

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Sugar crops as a solar energy converter*

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Biomass crops are renewable resources with multiple uses that can benefit mankind[1]. Current attention centers on replacement of petroleum as a principal source of energy for transportation applications. Fuels for electric power generation and household heating and/or cooking also are needed. Rising global demand for chemicals, food, construction materials, and paper products increase resource requirements even further.

Sugar crops are of special interest as solar energy converters because effective use of these renewable resources can make available the multiple products that will be required to ameliorate the crises affecting the availability of materials and fuels. Sugar crops achieve high yields, grow in many countries, and can be converted into desirable fuels, chemicals, and other products by application of relatively simple technology. Although sugar crops lack some of the glamour of hydrocarbon crops or aquatic crops, rapid changes are occurring in the technology for growing, processing, and converting these crops into useful products.

1. Sugar crop agriculture

The 3 major sugar crops are sugarcane (*Saccharum officianarum* L.), the sugar beet (*Beta vulgaris* L.), and sweet sorghum (*Sorghum bicolor* L. Moench). These sugar crops are compared with respect to their botanical characteristics, production requirements, current and possible yields, and compositions in the table. This comparison is necessarily oversimplified because special cultivars, production methods (e.g., drip irrigation), or environmental constraints could drastically change the tabular entries for specific geographical areas. For additional in-depth information, the interested reader is referred to some recent reviews on sugarcane[2,3], sugar beets[4], and sweet sorghum[5-7].

Sugarcane is a very high yielding crop that grows well in the wet tropics. Because it can be 'ratooned' (regrown from the plant material left in the ground following harvest), frequent investment in expensive planting operations is not required. The sugar juice is rich in sucrose and is readily crystallized. Therefore, this crop which is already a favorite of tropical less developed countries (LDCs) as a means of earning foreign exchange through sale of raw sugar offers excellent prospects as a source of fermentable sugars for production of fuels and chemicals[8].

The sugar beet presents quite a different picture. It grows best in temperate climates which includes many of the industrialized nations but few LDCs. Each crop requires a separate planting operation. The destruction of sugar beets by pests and diseases necessitates rotation with other crops[4], a distinct disadvantage compared with either sugarcane or sweet sorghum. The low fiber content of sugar beet is a disadvantage because not enough fibrous residues are available to generate the process steam required for ethanol production. However, the sugar beet fiber is a highly attractive cattle feed which is a source of cash revenue. The root of the sugar beet is a sugar-containing organ which is much more storable than is the stalk of either sugarcane or sweet sorghum.

Sweet sorghum resembles sugarcane in that the stalk storage organ contains appreciable sugar and ample fiber to generate process steam[9]. However, sweet sorghum differs markedly from sugarcane in that it is planted from seed and grows to maturity in from 3 to 6 months. The short growing season allows this tropically adapted plant to be grown in geographical areas with temperate climate during their warm season. In this respect, sweet sorghum resembles maize. Although sweet sorghum has been grown for more than 100 years on relatively small land holdings, the status of the crop development is far behind sugar beet and sugarcane. This crop is highly attractive for future development because yield improvement through conventional breeding and genetic engineering can be expected to parallel the achievements with maize.

Sweet-stemmed grain sorghum is a close relative of sweet sorghum in which the sugars that are synthesized are stored partly in the stalk as simple sugars and partly in the grain head as starch[6,7]. This dual storage of photosynthate permits part of the crop to be processed immediately and another part to be stored as readily as is maize or conventional grain sorghum.

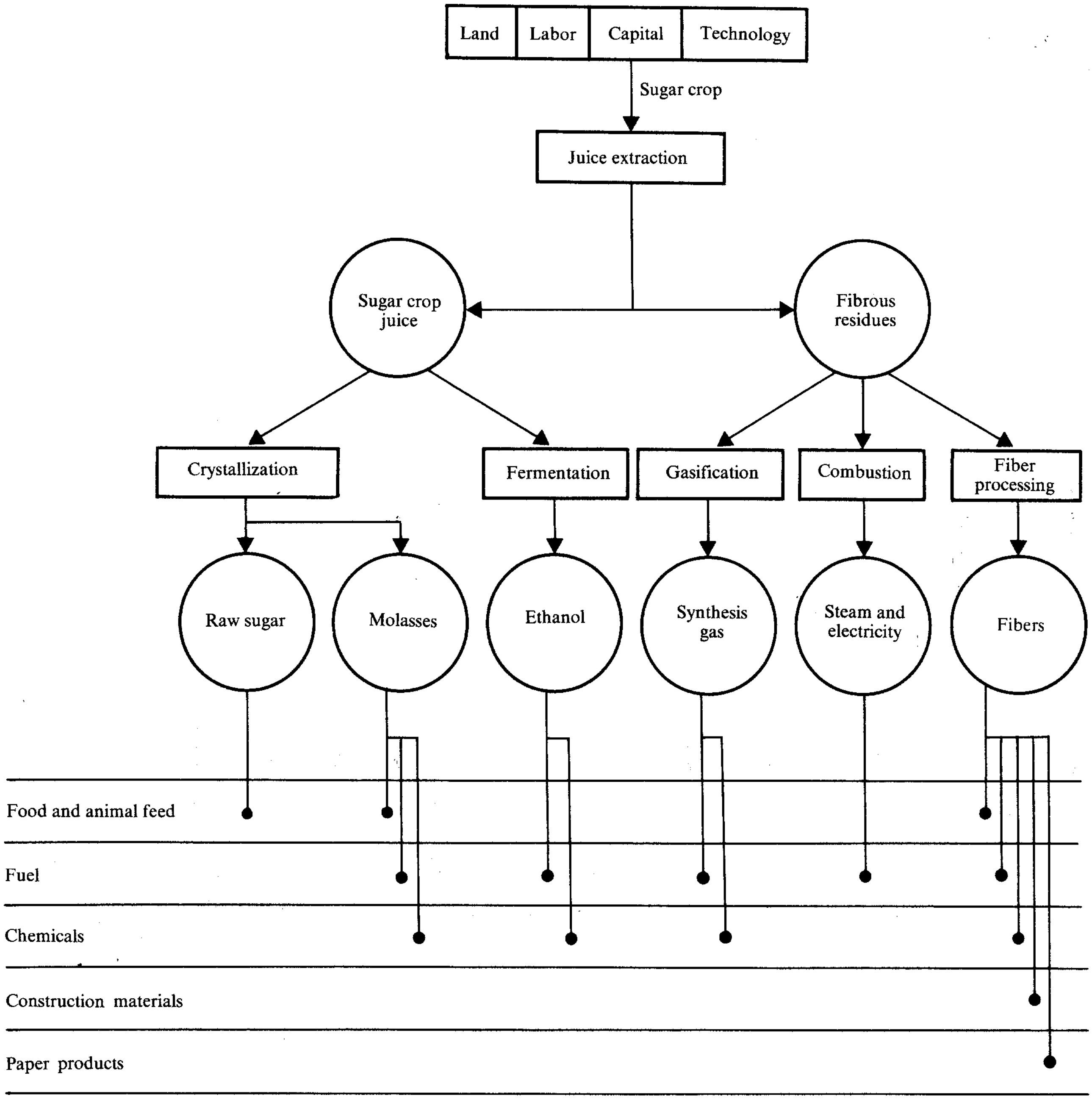
2. Sugar crop processing and conversion

As shown in the figure, sugar crops are renewable resources that are created from land, labor, capital, and technology. The millable stalks or beets are transported to a facility whereby juice is obtained for processing into raw sugar or into ethanol or other chemicals. The fibrous beet residues are immediately useful as cattle feed. Sugarcane or sweet sorghum fibrous residues, known as bagasse, can be converted to steam or electricity to perform milling operations, juice evaporation, distillation of fermented sugar solutions, or drying of fiber products. Only about 50% of the fiber is needed to achieve energy self-sufficiency at the processing facility, if modern steam and electricity generation technology is employed. Fiber remains for conversion into construction materials such as plywood substitutes or pulp for paper making or synthesis gas for energy or chemical markets.

Both juice processing and fiber processing facilities are capital intensive and involve economies of scale. Therefore, not all of the technologies shown in the figure necessarily can be carried out at any given location. Where the intent is to ferment sugar crop juice rather than prepare food grade raw sugar, there are opportunities to reduce investment in milling and other juice extraction equipment. This approach is exemplified by the Envirogenics process[10] and in the Ex-Ferm process[11]. Alternatively, the Tilby process[12,13] involves capital equipment investment roughly equal to conventional technology but aims at higher quality plywood substitutes to compensate for the investment.

Interest in sugar crops as solar energy converters has focused on production of ethanol by fermentation of the dilute sugar solutions obtained from sugar crops or from the molasses by-product that occurs in raw sugar production. Technologically, this conversion route is quite appropriate because very little of the energy content of a sugar crop juice is lost when the fermentable sugar is converted into ethanol and carbon dioxide[14]. The effect is to convert a virtually noncombustible material into an effective liquid fuel with a high octane rating. Whether the conversion of sugar crop juice into ethanol is desirable economically as well as technologically depends on the price of raw sugar and molasses and on the willingness of customers to accept larger quantities of these products. When sugar sells for \$0.60/kg, a liter of ethanol with a selling price of less than \$0.50 per liter consumes enough sugar to make \$1.00 worth of raw sucrose. Therefore, it may be more desirable to develop chemical products or fuels from bagasse while selling the simple sugars in food and feed markets. In many LDCs, charcoal is a major cooking fuel in rural areas. Pelletized bagasse could be a strong competitor as a fuel material because charcoal production involves the loss of much of the energy contained in the biomass resource[15].

Major trends in fermentation technologies that are relevant to sugar crops are aimed at cost reduction at every stage of the conversion process. For example, Kirby and Mardon have found that ethanol can be produced in high yields from coarsely ground sugar beets without the necessity for diffusion or other juice extraction processes[16]. This 'solid state' fermentation is said to yield a more concentrated ethanol solution. Similar experiments have been carried out on the pith



Overview of sugar crop processing systems.

of sweet sorghum. These approaches are related to the Envirogenics[10] and Ex-Ferm[11] processes mentioned previously.

The tower fermenter converts soluble sugars into ethanol in a fixed bed of yeast. The need for numerous fermenter vats is eliminated. Development of this technology requires not only the appropriate hardware but also the development of yeast with the appropriate physical properties (e.g., flocculation rate) to facilitate the process[17]. Fermentation times of 20-30% of batch fermentation times have been achieved readily with tower fermenters.

Fermentation rates are adversely affected by the toxic effects of the ethanol product on the yeast that manufactures ethanol. In recent years, several processes have been proposed and placed under development that involve removal of ethanol by vacuum distillation before it reaches a toxic concentration[18]. The initial embodiments of this concept involve continous removal of the ethanol but problems have been encountered in maintaining the appropriate vacuum when large quantities of CO_2 are evolved at the same time. More recent efforts have included staged processing in which the partially fermented broth is degassed, ethanol removed by vacuum distillation, and the broth is returned for continued fermentation[19,20].

Although yeasts have many advantages as sources of ethanol from sugar crops, other microorganisms have been found to perform this conversion much more rapidly and to function in the presence of higher concentrations of ethanol. The microorganism receiving the greatest attention at present is *Zymomonas* which is under investigation in numerous laboratories[21].

The solar energy conversion process that uses a sugar stalk crop as a collector generates at least as much lignocellulose as simple sugars. More than 70% of the lignocellulose consists of polymers of hexoses and pentoses, with the rest being lignin, waxes, and other materials[22]. If the pentoses and hexoses could be converted to ethanol, the sucrose could still be sold in high value food markets but energy products also could be made from these sugar stalk crops. Recent trends in lignocellulose research and development are greatly increasing the probability that this approach will be used for energy production before the year 2000. For example, a process is under development at MIT that involves direct fermentation of lignocellulose by *Thermocellum* microorganisms[23]. The result is production of ethanol from both cellulose and hemicellulose without need for pretreatment. Alternative approaches include a wide variety of pretreatments that involve fractionation of lignocellulose into

Comparison of sugar crops

Characteristic	Crop Sugarcane	Sugar beets	Sweet sorghum
1. Botanical family and carbon fixation pathway	Gramineae (C-4 pathway)	Chenopodiaceae (C-3 pathway)	Gramineae (C-4 pathway)
2. Sucrose storage organ	Stalk	Root	Stalk
3. Propagation method	Cutting, every 3-12 years	Fruit or seed, in rotation with other crops	Seed
4. Temperature requirements	Tropically adapted (21-40 °C), high freeze damage risk	Temperately adapted (16-28 °C)	Tropically adapted (18-40 °C)
5. Moisture requirements	3 cm rainfall yields 1 ton millable stalks (150+ cm for good yields) wide range	More than 50 cm of rainfall	More than 45 cm rainfall
6. Soil requirements	Sandy loams to heavy clay pH 4.5-8.0	Loams to heavy soils preferred ideal pH = 6.0-7.5. Poor performance in acid soil	Loams and sandy loams, relatively salt tolerant
7. Length of growing season	8-24 months	6-10 months (biennial)	3.5-6 months
8. a) Average yields (wet) b) Average yields (dry)	56-100 ton/ha · yr 15-27 ton/ha · yr	30 ton/ha · yr 6.6 ton/ha · yr	33-44 ton/ha · season 10-13 ton/ha · season
9. Possible yields (wet)	160 ton/ha · yr	65 ton/ha · yr	120 ton/ha · 6 month crop season
10. Typical composition of millable sugar storage organ	Water = 73% Soluble solids = 13% Fiber = 14%	Water = 78% Soluble solids = 16% Fiber = 6%	Water = 70% Soluble solids = 12% Fiber = 18%
11. Typical composition of soluble solids	Sucrose = 85% Glucose = 3.5% Fructose = 3.5% Nonfermentables = 8%	Sucrose = 75% Glucose = 4% Fructose + 4% Nonfermentables = 17%	Simple sugars = 70% (a) Nonfermentables = 30%

a) Sweet sorghum cultivars range widely in content of sucrose versus invert sugars (glucose and fructose) due to development of 'sugar' types and 'syrup' types and environmental conditions during sugar biosynthesis and storage.

lignin, cellulose, and hemicellulose. Steam explosion[24,25], destruction of the lignocellulose complex with lignin solvents[26], and destruction of the lignocellulose complex with cellulose solvents[27] are the 3 major thrusts in pretreatment. It is still too early to determine which approach is likely to be commercially viable.

These developments in the production of ethanol from lignocellulose do not render obsolete the production of ethanol from sucrose and other simple carbohydrates elaborated by sugar crops. Rather, they provide the opportunity for an evolution in which facilities are first constructed to make ethanol from the simple sugars and gradually converted to make use of sugar derived from the lignocellulose. The sucrose content then can be employed in food applications.

Most research and development concerning sugar crops are concerned with increasing yields, improving the energy balance, and reducing milling costs. However, the large scale manufacture of ethanol from sugar crops poses an ecological threat that is requiring increasing research attention. When ethanol is obtained by distillation, approximately 10-15 l of liquid effluent of high pollutant characteristics ('stillage') is obtained for each l of ethanol. Brazil's experience[28] with this stillage indicates that it represents a serious pollution problem. Research is under way in many laboratories but no fully satisfactory answers have been found yet. Typical methods for stillage disposal include: evaporation to dryness for use as fertilizer or animal feed[29], incineration to obtain fertilizer salts[29], spray irrigation, and anaerobic digestion to produce methane[30].

3. *Prognosis*

Sugar crops appear quite attractive as renewable resources for fuels, foods, chemicals, and other products. The attractiveness is based on firm agronomic foundations involving high yields of simple carbohydrates with valuable properties. These valuable properties include the nutritional and food functional values of sucrose and the fermentability of sucrose/invert sugars. The sugar crops with the best prospects as multiuse resources also contain large quantities of lignocellulose that provide both energy self-sufficiency for processing facilities and a raw material for numerous products based on the fiber, chemical, or energy content of this lignocellulose. Sugar crops will not displace trees or maize as major renewable resources but they will stand as full partners.

The reason for constructing sugar crop production and processing complexes is likely to remain the production of raw sugar to satisfy the steadily rising demand for this basic foodstuff throughout the world. Energy uses of this multiple-use resource will be sources of additional income rather than the reason for engaging in sugar crop production. In other words, sugar crops will not be energy crops but will be food crops with energy by-products.

Ethanol production from sugar crops is likely to grow, especially where stimulated by national energy self-sufficiency programs. Ethanol production can be employed to combat periodic raw sugar surpluses and to consume molasses in areas remote from cash markets for this cattle feed. In countries seeking to achieve self-sufficiency in ethylene-based chemicals, ethanol from sugar crops could provide the basis for an indigenous small-scale-ethylene industry. As with ethanol for motor fuel, national policies and subsidy programs would determine whether such an approach which is technically feasible is economically desirable. Any lignocellulose not needed for achievement of energy self-sufficiency for the ethanol facility could be used as a replacement for charcoal in countries where this cooking fuel is a major expenditure for low income families. Recent trends in fermentation research on lignocellulose indicate that some of the substantial lignocellulose by-product of raw sugar production may be of a source of ethanol.

The sugar crops provide an enormous challenge to those who support and conduct research and development on this planet. These crops and their products could become renewable resources for many countries that otherwise have few resources. The development of sugar crop systems to provide foods, fuels, chemicals, and other products from both the simple sugar constituents and the lignocellulose constituents should have high priority, especially for LDCs. Here, the issue is not food versus fuel – the system generates food, fuel, and cash to promote development.

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Plants as a direct source of fuel*

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Summary. Euphorbia lathyris, a plant which has been proposed as an 'energy farm' candidate yields a total of 35% of its dry weight as simple organic extractables. Chemical analyses of the extracts show that 5% of the dry weight is a mixture of reduced terpenoids, in the form of triterpenoids, and 20% of the dry weight is simple sugars in the form of hexoses. The terpenoids can be converted to a gasoline-like substance and the sugars can be fermented to alcohol. Based on a biomass yield of about 25 dry tons ha^{-1} $year^{-1}$, the total energy that can be obtained from this plant in the form of liquid fuels is 48 MJ ha^{-1} $year^{-1}$, 26 MJ in the form of hydrocarbons and 22 MJ in the form of ethanol. A conceptual process study for the large scale recovery of *Euphorbia lathyris* products indicates that this crop is a net energy producer. Several lines of investigation have been started to increase the hydrocarbon yield of this plant. Tissue cultures of *E. lathyris* have been established and will be used for selection, with the aim of regenerating a superior plant. Biochemical studies have been initiated to elucidate regulation of terpenoid metabolism. Future plans include eventual genetic engineering to select the most desirable plant for hydrocarbon production.

Introduction

We have undertaken the investigation of how green plants, such as certain *Euphorbia* species, serve as renewable resources for hydrocarbon production. All higher plants fix CO_2 into carbohydrates. However, there are a number of plant species which can reduce CO_2 further to hydrocarbon-like compounds. A well known plant is *Hevea,* the rubber tree, which belongs to the family Euphorbiaceae. In this family of plants, the genus *Euphorbia* consists of approximately 2000 species, ranging from small herbs and succulents to large trees, the large majority of which produce a milky latex which is often rich in reduced isoprenoids. In general, this genus grows well in semiarid climates. Most of the Euphorbias are native to various parts of Africa but have been found elsewhere throughout the world. At least 20 species are found in South Africa, another half dozen or so in Morocco and Ethiopia and several other candidates for oil producers are indigenous to the Canary Islands. 3 of the wild species which grow in the area of Tenerife, Canary Islands, are shown in figure 1 *(E. regis jubae, E. balsamifera* and *E. canariensis).*

We have chosen *Euphorbia lathyris,* a biennial shrub that grows wild in California as a potential 'energy farm' candidate (fig.2). *E. lathyris,* like many other