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CHAPTER 19

ECONOMIC OUTLOOK FOR THE PRODUCTION OF ETHANOL FROM FORAGE PLANT MATERIALS

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The potential of solar biotechnology is immense, not only for liquid fuels, but also for the range of petrochemical substitutes that can be produced by fermentation [1]. Since fermentation based on easily fermentable substrates such as sugar and starch is established, these materials are being used to produce ethanol for gasohol in the near term. However, the feedstock cost represents a large fraction (more than 50%) of the cost of producing ethanol. If grain prices were to rise dramatically, the final product cost of ethanol would soar. An alternative and relatively cheap substrate is lignocellulose. The processing technology, however, is not fully developed as yet. Lignocellulose is not readily converted because of cellulose crystallinity and also since lignin shields cellulose and hemicellulose from attack by enzymes. The only biological process which has been operated successfully at greater than the bench scale is based on municipal solid waste. In the Emert process [2], ethanol (190 proof) has been produced at 284 liter/day (75 gal/day) from about 1 metric ton/day of waste. The development of alternative processing technology using

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thermophilic anaerobes, for converting lignocellulose directly to ethanol is being pursued [3,4]. Most cost analyses predict an ethanol production cost well above $0.40/l [5,6].

In herbaceous plant materials, cell walls are composed of cellulose, lignin, hemicellulose and minor amounts of gums, pectins and other compounds. The major barrier to efficient hydrolysis of cellulose, either by acid or with enzymes, are complexes of lignin and hemicellulose with cellulose. While covalent bonds between these components have been demonstrated [7], limitation of hydrolysis is thought to be primarily due to sheathing of cellulose microfibrils with the lignin-hemicellulose matrix [8]. Access of the hydrolysis catalyst and reactants to the glucosyl linkages is retarded until lignin is removed. Because of the high cost of reducing lignocellulosic complexes to hydrolyzable form, it would seem reasonable to utilize sources of cellulose with minimal lignin content. During the growth and development of plant cells, lignification occurs at a stage after cellulose biosynthesis [9]. This fact suggests that immature vegetable parts of plants may be a source of readily available cellulose.

The possibility of using sorghum fiber for biomass and for paper-making pulp has already prompted numerous agronomic and chemical studies [10–12]. Sweet sorghum is attracting interest in this respect in all agriculturally productive regions of the United States; high-sucrose hybrids suitable even for the northern states are now available. Potential for utilizing sucrose invert sugar and starch as substrates for ethanolic fermentation and for utilizing the fiber as a source of fuel energy, or alternatively, of synthetic gas is promising but is hampered by the relatively poor storability of harvested cane [13]. The practice of ensiling forage materials has interesting potential as a means of storage of the fiber feedstock for alcohol production schemes. During ensiling, the organic acids produced from soluble sugars by the *Lactobacillus* and *Streptococcus* bacteria may cause hemicellulose-lignin sheathing to break down. As a result, the accessibility of water to cellulose for hydration and of enzymes for hydrolysis is reportedly improved [14].

The experimental basis for the economic study described in this chapter consisted of obtaining samples of selected herbaceous plant species and subjecting them to enzymatic hydrolysis. The results of this work have been previously reported [15]. Our objective is to provide a preliminary economic assessment of the alcohol fermentation potential of these species based on projected yields and laboratory results.

METHODOLOGY FOR ECONOMIC ASSESSMENT

Ethanol production costs were obtained for a process similar to the Natick process [6]. A simplified diagram of the processing operations is

shown in Figure 1. The process consists of mild mechanical size-reduction of the biomass, cellulase production, enzymatic hydrolysis of the lignocellulosic materials, filtration of the undigested solids and production of 95% ethanol using conventional yeast fermentation and distillation technology. Enzyme hydrolysis is assumed to occur over a 48-hr period at an enzyme load of 10 IU/g of substrate and without enzyme recycle.

While the laboratory hydrolysis data reported in this paper was obtained at an enzyme load of 86.7 IU/g of substrate, it was found that hydrolysis performed at an enzyme load of 8.7 IU/g of substrate over a period of 48 hr gave 95% of the original values. It is thus felt that the hydrolysis conditions used for the plant design will be representative of the laboratory data.

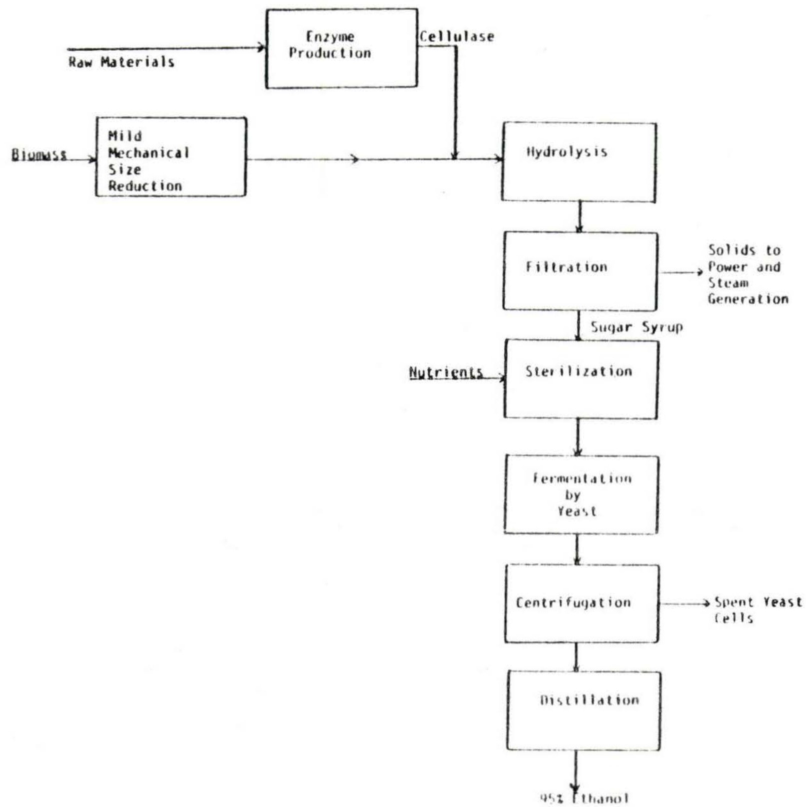

Figure 1. Simplified process flow diagram for ethanol production from vegetative forage crops.

Forage biomass culturing and harvesting costs were charged according to Saterson et al. [16] at the following levels:

- alfalfa, \$26.78/metric ton
- sudangrass, \$17.75/metric ton
- sorghum (any type), \$22.71/metric ton

where the sudangrass cost was estimated assuming an average forage yield of 22.15 metric ton/ha [16] and the same harvesting costs as for sorghum. Figure 2 shows two of the species selected for this analysis.

A preliminary economic evaluation ($\pm 25\%$) was then performed using the Natick information [6]. Since the sole experimental data available were on the 24-hr sugar yield from the enzymatic hydrolysis of the forage material, it was felt that a complete plant design would be unreliable and somewhat premature at this time. The evaluation was then based on the assumption that the cost of producing 1 liter of 95% ethanol (without charge for the cellulosic substrate) would be a constant and independent of the substrate. This assumption essentially means that, as long as the sugars are in the soluble form, the cost of producing ethanol is the same no matter what the sugar source is.

The cost of ethanol production was \$0.35/l (\$1.32/gal), according to the Natick report [6], at 1978 prices and with no substrate cost included. To generate the ethanol production costs for our analysis, the Marshall & Stevens index was used to update the equipment costs to the third quarter of 1979. An index of 545.3 for 1978 and of 606.4 for the third quarter of 1979 was used [17]. Pretreatment charges were calculated based on Nystrom's estimates [18] assuming that the substrate would pass through a ball-milling size reduction to 40 mesh before enzymatic digestion. Although detailed pretreatment studies were not performed in this project, it is believed that the pretreatment costs as calculated here are fairly conservative, and an even milder pretreatment may result in similar cellulose conversion during enzyme hydrolysis. Labor costs were increased at a rate of 7%/yr over the Natick data. The remaining items were calculated on the same basis as in the Natick analysis:

- depreciation - 10%/yr of total fixed investment
- plant onstream factor - 330 days/yr
- plant overhead - 80% of total labor cost
- taxes and insurance - 2%/yr of total fixed investment

To obtain the total production cost a substrate charge was added to this cost as calculated according to the following formula:

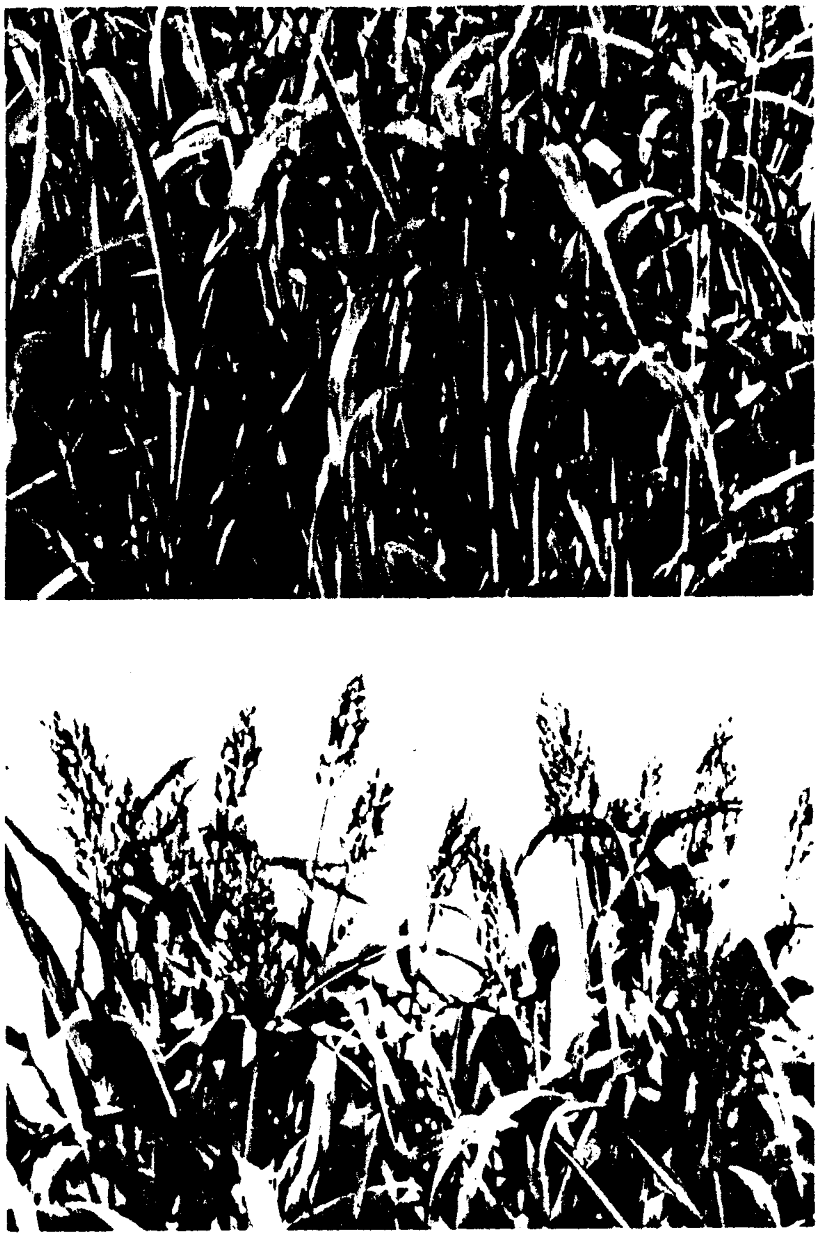

Figure 2. Field-grown sudangrass (top) and forage sorghum (bottom), representing two of the species used in these studies (provided by DeKalb AgResearch, Inc.).

$$\text{substrate charge } (\$/\text{l of } 95\% \text{ ethanol}) = \frac{\text{forage crop cost } (\$/\text{metric ton})}{\text{glucose yield } (\text{kg/metric ton}) \times \text{ethanol conversion } (\text{kg/kg}) \times (1 \text{ liter ethanol}/0.789 \text{ kg})}$$

The main limitation of this economic analysis lies in the fact that a 10% glucose syrup after hydrolysis as assumed in the Natick study may not be possible for all the forage materials included in this work using an enzyme load of 10 IU/g of substrate. This would make a concentration step necessary in some cases; however, since no data were available on the maximum substrate charge possible on the hydrolyzer, no calculations were made in this study for this purpose.

RESULTS AND DISCUSSION

Experimental

Lignin content is related directly to plant maturity. The conversion of the cellulose component of forage crops to glucose by enzymatic hydrolysis is related inversely to the lignin content. Generally, hydrolysis of cellulose from young plant tissues is superior to that from mature tissues. In Tables I and II and the following paragraphs are presented examples of these findings from studies on alfalfa, sudangrass, sorghum silage and brown-midrib sorghum mutants.

Mature alfalfa tissue contains proportionally more lignin than does younger tissue. The percent conversion of cellulose proportionally varies from 41% for the most mature tissue to 84% for the youngest parts of the plant. Fermentable sugar yields from the most easily hydrolyzed top segment of the plants are, however, less than those from the mature bottom segment because of the higher cellulose content of the bottom fraction.

Studies on whole plant samples of half-grown and mature sorghum supported the stated relationships between maturity, lignin content and cellulose hydrolysis. As an example, mature sorghum with 6.5% lignin gave 31% of the theoretical conversion of cellulose while vegetative material with 3.1% lignin gave 47% conversion. Mature sorghum, but not vegetative sorghum, contains considerable fermentable sugars which are extractable from leaves and stalks. The differences were compensating and resulted in similar glucose yields after cellulolytic hydrolysis of mature and of vegetative sorghums.

Ensiling would provide a means of storage of vegetative feedstock and

Table I. Enzymatic Hydrolysis Products and Theoretical Conversion of Cellulose to Glucose from Forage Crops at Various Stages of Maturity

	Total Glucose	Extractable Glucose	Net Hydrolysis[a]	Cellulose Conversion[b]
	(mg glucose/g dry substrate-day)			(%)
Dekalb FS-25A + Sorghum				
Vegetative	155	0	155	47
Mature	151	57	94	31
Silage	188	0	188	71
Frontier 214 Sorghum				
Vegetative	103	0	103	34
Silage	175	0	175	68
Sudangrass, Vegetative	204	64	140	56
Brown-Midrib Mutants of Sorghum (vegetative, field-grown)				
bmr_6	215	61	154	75
bmr_{12}	251	80	171	77
bmr_{16}	236	84	152	68
bmr_{17}	257	74	183	89
bmr_{18}	288	69	159	70
Alfalfa (first cutting, vegetative)				
Top	NA			
Next-to-top	NA			
Next-to-bottom	NA			
Bottom	128	5	123	43
Alfalfa (second cutting, vegetative)				
Top	89	0	89	84
Next-to-top	113	1	112	77
Next-to-bottom	131	1	130	55
Bottom	148	4	144	41

[a] By difference.
[b] Values obtained by dividing net hydrolysis by respective cellulose contents from Table II and multiplying by 100.

a biological process to improve the conversion of constituent cellulose. The hydrolysis of the silage of the same sorghum variety described above resulted in 71% theoretical cellulose conversion as compared to that from the mature sorghum equal to 31%. Since the lignin content of the silage was equal to that of the mature material, changes in the fiber structure resulting from ensiling apparently improve accessibility of enzymes to the fibers. Hydrolysis of the cellulose in silage may be enhanced by the action of organic acids (resulting pH ~3.8–4.5 in well-ensiled material)

Table II. Fiber Composition of Forage Sorghum Varieties (%, dry weight basis)[a]

	Cell-Soluble Material	Acid Detergent Fiber	Hemicellulose	Cellulose	Lignin
Dekalb FS-25A + Sorghum					
Vegetative	40.6	38.9	20.5	33.0	3.1
Mature	37.6	39.0	23.3	30.4	6.5
Silage	38.7	37.0	24.3	26.3	6.7
Frontier 214 Sorghum					
Vegetative	44.2	38.8	17.0	30.3	3.9
Silage	45.1	35.3	19.5	25.9	4.5
Sudangrass, Vegetative	45.6	29.7	24.7	25.2	3.1
Brown Midrib Mutants of Sorghum (vegetative)					
bmr_6	51.0	26.5	22.5	20.5	4.4
bmr_{12}	48.3	25.4	26.3	22.3	1.9
bmr_{16}	51.9	26.9	21.2	22.0	2.5
bmr_{17}	50.1	24.2	25.7	20.5	2.2
bmr_{18}	51.7	26.4	21.9	22.7	1.9
Alfalfa (first cutting)					
Top	68.0	26.9	5.1	18.6	7.8
Next-to-top	54.9	39.6	5.5	23.8	12.9
Next-to-bottom	49.0	45.4	5.6	26.7	13.6
Bottom	39.4	46.1	14.5	28.9	15.9
Alfalfa (second cutting)					
Top	83.5	15.8	0.7	10.5	4.8
Next-to-top	73.0	25.6	1.4	14.8	8.0
Next-to-bottom	56.8	39.1	4.2	23.7	10.3
Bottom	43.7	50.1	6.2	34.9	13.8

[a]Analysis by permanganate oxidation procedure of Goering and Van Soest [19].

on lignocellulosic structures over time. During enzymatic hydrolysis, the loss of the glucose product to the acid-forming *Lactobacillus* and *Streptococcus* bacteria was prevented by addition of 0.01% (w/v) of agricultural grade tetracycline hydrochloride. This level of antibiotic did not inhibit the fermentation of the hydrolyzed sugars by *Saccharomyces cerevisiae*.

Unlike sorghum, sudangrass in vegetative growth contained considerable amounts of sugars that were extractable from leaves and stalks. Cellulolytic hydrolysis added to the extractable 6.4% glucose and yielded a total of 20.4% fermentable sugar on a dry weight basis. This material

contained 3.1% lignin, and the cellulose was converted to 56% of theoretical.

Conversions of cellulose averaging 75% of theoretical were obtained from brown-midrib sorghum mutant lines. The average lignin content of these materials was 2.6%. The literature described mature brown-midrib mutants as having lignin content 61 percent lower than isogenic normal lines [20]. These mutants in vegetative growth contained 7.4% extractable glucose and on hydrolysis yielded a total of 23.7% glucose on a dry weight basis.

Economics

The results obtained by a detailed analysis of the bioconversion process of the various forage materials are shown in Tables III to VIII. Table III shows that the total fixed investment for a 95-million-liter/yr ethanol plant is estimated at about $59 million, or about $0.62/l of installed capacity, which is considered a reasonable figure by most of the researchers working in this area. Startup and working capital estimates bring the total capital investment to about $74 million.

Table IV presents a breakdown of the ethanol production costs from the forage crops without a substrate charge. The processing costs are estimated at $0.33/l, well below the $0.35–0.45/l range reported by other researchers [5,6]. Enzyme production is the major factor in the ethanol cost (47% of the total), followed by fermentation and distillation (26%), hydrolysis (15%) and pretreatment (12%). This finding stresses once more the need for strong research efforts in the area of cellulase production.

Table III. Estimated Capital Investment for a 95-million-liter/yr Ethanol Plant ($1,000s, Third Quarter 1979)

	Pretreatment	Enzyme Production	Hydrolysis	Ethanol Production	Total
Major Equipment	1,320	17,243	13,350	15,186	47,099
Offsite Investment	462	1,869	108	4,242	6,681
General Service Facilities	179	1,911	1,346	1,943	5,379
Total Fixed Investment	1,961	21,023	14,804	21,371	59,159
Startup (8.5% TFI)					5,029
Working Capital (16.5% TFI)					9,761
Total Capital Investment					73,949

Table IV. Cost (¢/l) Analysis, Ethanol from Cellulose[a]

	Pretreatment	Enzyme Production	Hydrolysis	Ethanol Production	Total
Total Material	1.40	8.88	0.35	0.51	11.14
Total Utilities	2.10	1.57	1.20	3.16	8.03
Total Direct Labor	0.20	1.37	0.82	1.30	3.69
Total Direct Cost	3.60	11.82	2.37	4.97	22.76
Plant Overhead	0.16	1.10	0.66	1.04	2.96
Tax and Insurance	0.04	0.44	0.31	0.45	1.24
Depreciation	0.21	2.22	1.56	2.26	6.25
Factory Cost	4.01	15.58	4.90	8.72	33.21
Percent Total Cost	12	47	15	26	100

[a]Basis: 95% ethanol, no substrate charge.

Estimates for the ethanol yield from the forage crops included in this study are shown in Table V. These estimates are based on a 45% ethanol yield from glucose during anaerobic fermentation. As expected, sudangrass and the brown-midrib mutants of sorghum show the highest potential with, respectively, 2583 and 2338 liters of ethanol/ha-yr. The ensiled sorghum materials show the second best possibility with an ethanol yield close to 1900 liter/ha-yr. Vegetative Frontier 214 sorghum and vegetative alfalfa rank at the bottom with respectively 1016 and 903 liters/ha-yr.

The estimated total production costs are shown in Table VI. These costs show that vegetative sudangrass and brown-midrib mutants of sorghum are the most promising substrates with the ensiled sorghum crops being the second best. Total ethanol production costs are now at least \$0.48/l, with alfalfa and Frontier 214 sorghum reaching \$0.72/l of 95% ethanol. A breakdown of the total production costs presented in Table VI can be seen in Table VII. It can be observed that substrate costs represent the major fraction of the total cost, ranging from a minimum of 31% to a maximum of 54%. Enzyme costs rank second, ranging from 22 to 33%, followed by fermentation and distillation costs, which vary from 12 to 18% of the total. Hydrolysis and pretreatment costs represent the minor fraction, varying from 5 to 10% each of the total production costs.

Table VIII shows the estimated total ethanol production costs for a fermentation yield of 50% (weight of ethanol/weight of glucose). As expected, a decrease in the production costs relative to those in Table VI is observed, reflecting the smaller quantity of forage raw materials required for the same ethanol production rate. The decrease averages about 3¢/l and reflects the high cost of the raw materials and the need for efficient substrate conversion at all stages of the process.

Table V. Estimated Ethanol Yields from Several Forage Materials[a]

Raw Materials	Total Glucose Yield (kg glucose/dry metric ton-day)	Substrate Yield (metric ton/ha-yr)	Ethanol Yield (liter/ha-yr)
Dekalb FS-25A + Sorghum			
Vegetative	155	17.3	1530
Mature	151	17.3	1490
Silage	188	17.3	1855
Frontier 214 Sorghum			
Vegetative	103	17.3	1016
Silage	175	17.3	1727
Sudangrass, Vegetative	204	22.2	2583
Brown-Midrib Mutants of Sorghum, Vegetative (average)	237	17.3	2338
Alfalfa, Vegetative (average)	120	13.2	903

[a]Basis: ethanol yield during glucose fermentation = 45% on a weight basis.

Table VI. Estimated Total Ethanol Production Costs from Several Forage Materials[a]

Raw Materials	Substrate Cost ($/metric ton)	Substrate Charge to Ethanol Cost ($/l 95% Ethanol)	Total Ethanol Production Cost ($/l 95% Ethanol)
Dekalb FS-25A – Sorghum			
Vegetative	22.71	0.26	0.59
Mature	22.71	0.26	0.59
Silage	22.71	0.21	0.54
Frontier 214			
Vegetative	22.71	0.39	0.72
Silage	22.71	0.23	0.56
Sudangrass, Vegetative	17.75	0.15	0.48
Brown-Midrib Mutants of Sorghum, Vegetative (average)	22.71	0.17	0.50
Alfalfa, Vegetative (average)	26.78	0.39	0.72

[a]Ethanol processing costs = 33.21¢/l (from Table IV). Ethanol yield during glucose fermentation = 45% on a weight basis.

Table VII. Relative Cost Factor Analysis of Ethanol Production Costs from Several Forage Materials[a]

Raw Materials	Substrate	Pretreatment	Enzyme Production	Hydrolysis	Ethanol Production
Dekalb FS-25A – Sorghum					
Vegetative	44	7	26	8	15
Mature	44	7	26	8	15
Silage	39	7	29	9	16
Frontier 214 Sorghum					
Vegetative	54	5	22	7	12
Silage	41	7	28	9	15
Sudangrass, Vegetative	31	8	33	10	18
Brown-Midrib Mutants of Sorghum, Vegetative (average)	34	8	31	10	17
Alfalfa, Vegetative (average)	54	5	22	7	12

[a]Figures given are % of total cost.

Table VIII. Estimated Total Ethanol Production Costs from Several Forage Materials[a]

Raw Materials	Substrate Charge to Ethanol Cost ($/l 95% EtOH)	Total Ethanol Production Cost ($/l 95% EtOH)
Dekalb FS-25A + Sorghum		
Vegetative	0.23	0.56
Mature	0.24	0.57
Silage	0.19	0.52
Frontier 214 Sorghum		
Vegetative	0.35	0.68
Silage	0.20	0.53
Sudangrass, Vegetative	0.14	0.47
Brown Midrib Mutants of Sorghum, Vegetative (average)	0.15	0.47
Alfalfa, Vegetative (average)	0.35	0.68

[a]Ethanol processing costs = 33.21¢/l (from Table IV). Ethanol yield during glucose fermentation = 50% on a weight basis.

CONCLUSIONS

The production of ethanol by fermentation of the glucose obtained via enzymatic hydrolysis of the vegetative forage crops considered in this study requires further research and development before economic feasibility can be attained. The total production costs ranges from $0.48/l for vegetative sudangrass to $0.72/l for vegetative alfalfa. These high costs are not totally unexpected, since the forage crops considered here have a high cash value. It should be noted that the costs obtained in this study do not account for the use of reducing sugars other than glucose and do not include any by-product credits. If these credits were included, the costs reported in this study could be lowered by as much as 14¢/l. Since only a mild pretreatment is required for the vegetative forage materials, processing costs are at least about 10% lower than other published processing costs [6]. This represents a considerable advantage of vegetative forage crops over other lignocellulosic materials.

Substrate costs constituted, in most instances, the major fraction of the total production costs, varying from 31 to 54%. In view of this, an efficient substrate conversion must be obtained at all stages of the process. Enzyme production costs were also very important, ranging from 22–33% of the total cost; this indicates the need for continued research

on cellulase production technology. The total capital investment for a 95-million-liter/yr ethanol plant was found to be about $74 million. This represents a fixed capital investment of about $0.62/l ethanol capacity. To reduce substrate costs, one might either look at less expensive means of culturing and harvesting the crops or coupling to other operations. Examples could be coupling alfalfa hydrolysis to a soluble protein extraction operation or harvesting sorghum grain and stalks simultaneously but separately. Alternatively, one may obtain other substrates whose culture is indigenous to a growing area. Such unconventional plants may have the same processing costs, yet may be obtained for 0–3¢/l of ethanol.

These studies were definitive in showing how hydrolysis and endogenous sugar levels influence the yield of fermentable sugar. This yield is also proportional to the biomass yield. Saterson et al. [16] in work supported under a Department of Energy contract to A. D. Little Coporation and Jackson [21] at Battelle Columbus Laboratories screened herbaceous plants for potential biomass production in 10 regions of the contiguous United States. Many were plants whose culture was indigenous to a growing area. Some were unconventional as food and forage crops, but were good candidates in terms of their projected biomass production potential. Crops appropriate for the Great Plains included 14 species of grasses and legumes and 9 species of unconventional crops and/or weeds. The comparative analysis of Heichel of cultural energy requirements placed such crops high with respect to total energy yield [22]. Sweet sorghum rated highest in that study, but in terms of practical energy recovery, cane storage and juice expression present major difficulties at present [13]. Future crops for alcohol fermentation may include other traditional food crops, certain weeds, syrup sorghum, Jerusalem artichoke and forage grasses. The latter are adapted to a wider range of growing conditions than other crops and are the more productive under adverse conditions. Since they are grown primarily for plant material they are more likely to produce significant yields of biomass than other crops. Warm-season grasses possess the more efficient photosynthesis route, permit multiple cuttings which maintain the plant at a high rate of photosynthesis for a large part of the growing season, have low water requirements, and their culture requires less energy than other crops. The use of such crops as raw materials may bring the cost of fermentation ethanol down to the economically viable range.

The high cost of feedstock is a major barrier to the conversion of biomass to alcohol fuels [4]. To reduce substrate costs, one must optimize the efficiency of either production or conversion. Production costs are reduced when yields are increased, when means of culturing and harvesting are the most energy efficient in terms of cultivation, irrigation and fertilization, and when the harvesting costs can be discounted, as with the simultaneous collection of grain and straw. Conversion costs are reduced when the biomass requires no pretreatment to obtain high percentages of cellulose hydrolysis, when a significant proportion of the plant dry matter is soluble fermentable sugar, and when the fermentation system can utilize both cellulose and hemicellulose hydrolysis products. For these reasons, it is important to study simultaneously the agronomic and biochemical aspects of a potential biological conversion feedstock as a production-conversion system [1]. An advantage gained by the production of great quantities per unit area of biomass is offset if the cellulose is resistant to hydrolysis. On the other hand, materials containing relatively little lignin can be hydrolyzed very efficiently and would be very attractive as feedstock if biomass yields were reasonable. The balance between the potential for production and conversion must be known in a controlled comparative experimental setting.

SUMMARY

In this research project, we have tested vegetative alfalfa, vegetative sudangrass, and vegetative, mature and ensiled sorghum species as possible feedstocks for ethanol production. Results were presented for the yield of sugars via cellulose hydrolysis of these materials and for the projected alcohol production costs for a 95-million-liter/yr plant. These costs ranged from \$0.48/l for vegetative sudangrass to \$0.72/l for vegetative alfalfa. Substrate costs comprised the major fraction of the total cost. This leads to the conclusion that feasible process economics depend on options such as use of unconventional crops, stillage protein credit, cohydrolysis of starch in immature grain component and sharing of feedstock production cost with mature grain harvest.

REFERENCES

1. Villet, R. H. *Biotechnology for Producing Fuels and Chemicals from Biomass: Recommendations for R&D, Vol. 1*, SERI/TR-332-360 (Golden, CO: Solar Energy Research Institute, 1979).
2. Emert, G. H., and R. Katzen. "Chemicals from Biomass by Improved Enzyme Technology," in *Biomass as a Nonfossil Fuel Source*, D. L. Klass, Ed. (Washington DC: American Chemical Society, 1981), pp. 213-225.

3. Wang, D. I. C., I. Biocic, H.-Y. Fang and S.-D. Wang, "Direct Microbiological Conversion of Cellulosic Biomass to Ethanol," in *Proceedings of the Third Annual Biomass Energy Systems Conference* (Golden, CO: U.S. Department of Energy, 1979), p. 61.
4. Pye, E. K., and A. E. Humphrey. "Production of Liquid Fuels from Cellulosic Biomass," in *Proceedings of the Third Annual Biomass Energy Systems Conference* (Golden, CO: U.S. Department of Energy, 1979), p. 69.
5. Wilke, C. R., R. D. Yang, A. F. Sciamanna and R. P. Freitas. "Raw Materials Evaluation and Process Development Studies for Conversion of Biomass to Sugars and Ethanol," paper presented at the Second Annual Symposium on Fuels from Biomass, Troy, NY, June 20-22, 1978.
6. Spano, L., A. Allen, T. Tassinari, M. Mandels and D. Y. Ru. "Reassessment of Economics of Cellulase Process Technology: For Production of Ethanol from Cellulose," paper presented at the Second Annual Symposium on Fuels from Biomass, Troy, NY, June 20-22, 1978.
7. Morrison, I. M. "Structural Investigations on the Lignin-Carbohydrate Complexes of *Lolium perenne*," *Biochem. J.* 139:197-204 (1974).
8. Polein, J., and B. Bezuck. "Investigation of Enzymatic Hydrolysis of Lignified Cellulosic Materials," *Wood Sci. Technol.* 11:275-290 (1977).
9. Esau, K. *Plant Anatomy*, 2nd ed. (New York: John Wiley & Sons, Inc., 1953).
10. White, G. A., T. F. Clark, J. P. Craigmiles, R. L. Mitchell, R. G. Robinson, E. L. Whiteley and K. H. Lessman. "Agronomic and Chemical Evaluation of Selected Sorghums as Sources of Pulp," *Econ. Bot.* 28:136-144 (1974).
11. Crookston, R. K., C. A. Fox, D. S. Hill and D. N. Moss. "Agronomic Cropping for Maximum Biomass Production," *Agron. J.* 70:899-902 (1978).
12. Schmidt, A. R., R. D. Goodrich, R. M. Jordan, G. C. Marten and J. C. Meiske. "Relationships among Agronomic Characteristics of Corn and Sorghum Cultivars and Silage Quality," *Agron. J.* 68:403-406 (1976).
13. Lipinsky, E. S., S. Kresovitch, T. A. McClure and W. T. Lawhon. "Fuels from Sugar Crops," report to U.S. DOE, TID-28191 (1978).
14. Leatherwood, J. M., R. E. Mochrie, E. J. Stone and W. E. Thomas. "Cellulose Degradation by Enzymes Added to Ensiled Forages," *J. Dairy Sci.* 46:124-127 (1963).
15. Linden, J. C., A. R. Moreira, D. H. Smith, W. S. Hedrick and R. H. Villet. "Enzymatic Hydrolysis of the Lignocellulosic Component from Vegetative Forage Crops," *Biotechnol. Bioeng. Symp.* (10):199-212 (1980).
16. Saterson, K. A., and M. K. Luppold. "Herbaceous Screening Program—Phase I," DOE Contract ET-78-C-02-5035-A000 (1979).
17. "Marshall & Stevens Equipment Cost Index," *Chem. Eng.* 86(24):7 (1979).
18. Nystrom, J. "Discussions of Pretreatment to Enhance Enzymatic and Microbiological Attack of Cellulosic Materials," *Biotechnol. Bioeng. Symp.* (5):221-224 (1975).
19. Goering, H. K., and P. S. Van Soest. "Handbook No. 379," Agricultural Research Service, U.S. Department of Agriculture, Washington, DC (1970).
20. Fritz, J. O., R. P. Cantrell, V. L. Lechtenberg, J. C. Axtel and J. M. Hertel. "Fiber Composition and IVDMD of Three bmr Mutants in Grain

Grass Type Sorghums," *Abstr. Crop. Sci. Soc. Am. Ann. Mtg.* (1979), p. 128.
21. Jackson, D. R. "Common Weeds and Grasses May Prove to Be Valuable Sources of Energy," *Biomass Dig.* 1(11):2 (1979).
22. Heichel, G. H. "Energetics of Producing Agricultural Sources of Cellulose," *Biotechnol. Bioeng. Symp.* (5):43-47 (1975).