ECONOMIC OUTLOOK FOR THE PRODUCTION OF ETHANOL FROM FORAGE PLANT MATERIALS

A.R. Moreira and J.C. Linden

Department of Agricultural and Chemical Engineering
Colorado State University
Fort Collins, Colorado 80523

D.H. Smith

Department of Agronomy
Colorado State University
Fort Collins, Colorado 80523

R.H. Villet

Solar Energy Research Institute
Golden, Colorado 80401

SUMMARY

Lignocellulose is an immense potential resource for the production of ethanol and other fermentation chemicals and fuels. The recalcitrant nature, however, of this material due to the high cellulose crystallinity and the lignin barrier has tended to make the process economics unattractive. As an alternative to woody biomass, vegetative forage crops may be good substrates for ethanol fermentation due to their low lignin content.

In this research project, we have tested vegetative alfalfa, vegetative sudan grass and vegetative, mature and ensiled sorghum species as possible feedstocks for ethanol production. Results are presented here for the yield of sugars via cellulose hydrolysis of these materials and for the projected alcohol production costs for a 25×10^6 gallon/year plant. These costs ranged from $1.68/gallon for vegetative sudan grass to $2.58/gallon for vegetative alfalfa. Substrate costs comprised the major fraction of the total cost. This leads to the conclusion that a viable process economics depends on options such as the following: use of unconventional crops; stillage protein credit; co-hydrolysis of starch in immature grain component and sharing of feedstock production cost with mature grain harvest.

INTRODUCTION

Diminishing fossil fuel reserves and recent dramatic increases in crude oil prices have prompted the United States and other oil-importing nations to develop renewable sources of energy.

Solar energy could well contribute a significant portion of the United States energy consumption within the next decade. The potential in developing solar biotechnology is immense (1), not only for liquid fuels, but also for the range of petrochemical substitutes which can be produced fermentatively.

Ethanol has received considerable attention because it can be used as a clean-burning gasoline extender and octane-number improver. Moreover, since it can be converted to other chemicals, it is likely to become a key chemical feedstock for a renewable resources chemicals industry.

In the near term, since fermentation technology based on easily fermentable substrates (such as sugar and starch) is established, these materials are being used to produce ethanol for gasohol. But 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 the crystallinity in cellulose structure and also since lignin shields cellulose and hemi-cellulose 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 75 gallons/day from about 1 metric ton/day of waste.

The development of alternative processing technology using thermophilic anaerobes, for converting lig-ocellulose directly to ethanol is being pursued (3,4 for example). Most cost analyses predict an ethanol production cost well above $1.40/gallon (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 vegetative parts of plants may be a source of low lignin cellulose.

The possibility of using sorghum fiber for biomass and for papermaking pulp has already prompted numerous agronomic and chemical studies (10,11,12). 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 the sucrose invert sugar, and starch contents 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).

In the present work experimental results were obtained for the enzymatic hydrolysis of low-lignin forage materials (alfalfa, sudan grass and several species of sorghum) and a preliminary economic assessment for the alcohol fermentation of such hydrolyzates was made.

METHODOLOGY

The experimental basis for this study was conducted to determine whether biomass at an early vegetative stage of development was more readily hydrolyzed by cellulolytic enzymes than at the mature stage of development, which is characterized by extensive lignification. Representative samples of forage crop materials, including alfalfa, sudan grass and sorghum in vegetative and mature growth were assessed by the extent of enzymatic hydrolysis of lignocellulose to glucose as a function of cellulose and lignin content. Experimental materials and methods used to obtain quantitative information about forage composition and enzymatic hydrolysis have been detailed earlier (15).

Ethanol production costs were obtained for a process flow sheet similar to the Natick process (6). A simplified diagram of the processing operations is shown in Figure 1. The process consists of mechanical grinding 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-hour period at an enzyme load of 10 IU/gram 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/gram of substrate, it was found that hydrolysis performed at an enzyme load of 8.7 IU/gram of substrate over a period of 48 hours 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.

Forage biomass culturing and harvesting costs were charged according to Saterson _et al_. (16) at the following levels:

Alfalfa	----	\$26.78/MT
Sudan Grass	----	\$17.75/MT
Sorghum (any species)	----	\$22.71/MT

where the sudan grass cost was estimated assuming an average forage yield of 22.15 MT/ha (16) and the same harvesting costs as for sorghum.

A preliminary economic evaluation (± 25%) was then performed using the Natick information (6). Since the sole experimental data available was the 24-hour 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 gallon 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 \$1.32/gallon according to the Natick report (6), at 1978 prices and with no substrate cost included. In order 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). Labor costs were increased at a rate of 7%/year over the Natick data. The remaining items were calculated on the same basis as in the Natick analysis:

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

This analysis generated an ethanol production cost of \$1.11/gallon. This cost does not reflect any pretreatment charges since there is no need for pretreatment steps when using vegetative forage crop materials. To obtain the total production cost a substrate charge was added to this cost. This substrate charge was calculated according to the following formula:

$$\text{Substrate charge } (\$/\text{gallon } 95\%\text{ EtOH}) = \frac{\left(\text{Forage crop cost } \$/\text{MT}\right)}{\left(\text{Glucose yield kg/MT}\right)\left(\text{EtOH conversion kg/kg}\right)\left(\frac{1\ \ell\ \text{EtOH}}{0.789\ \text{kg}}\right)\left(\frac{1\ \text{gallon}}{3.783\ \ell}\right)}$$

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/gram of substrate. This would make a concentration step necessary in some cases; however, since no data was 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 1 and 2 and in the following paragraphs are presented examples of these findings from studies on alfalfa, sudan grass, 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 percent for the most mature tissue to 84 percent 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 percent lignin gave 31 percent of theoretical conversion of cellulose while vegetative material with 3.1 percent lignin gave 47 percent 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 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 percent theoretical cellulose conversion as compared to that from the mature sorghum equal to 31 percent. 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 (pH 4) on the 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 sorchum, sudan grass in vegetative growth contained considerable amounts of sugars which were extractable from leaves and stalks. Cellulolytic hydrolysis added to the extractable 6.4 percent glucose and yielded a total of 20.4 percent fermentable sugar on a dry weight basis. This material contained 3.1 percent lignin, and the cellulose was converted to 56 percent of theoretical

Conversions of cellulose averaging 75 percent of theoretical were obtained from brown mid-rib sorghum mutant lines. The average lignin content of these materials was 2.6 percent. The literature described mature bmr-mutants as having lignin content 61 percent lower than isogenic lines (19). These mutants in vegetative growth contained 7.4 percent extractable glucose and upon hydrolysis yielded a total of

23.7 percent 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 3 through 8. Observation of Table 3 shows that the total fixed investment for a 25 x 10^6 gallons/year ethanol plant is estimated at about 57 million dollars, or about $2/gallon of installed capacity which is considered a reasonable figure by most of the researchers working in this area. Start-up and working capital estimates bring the total capital investment to about 71 million dollars.

Table 4 presents a breakdown of the ethanol production costs from the forage crops, without a substrate charge. No pretreatment costs were included in this table since these materials do not require such pretreatment. As a consequence, the processing costs are estimated at $1.11/gallon, well below the $1.30-$1.75/gallon range reported by other researchers (5,6). Enzyme production is the major factor in the ethanol cost (53% of the total), followed by fermentation and distillation (30%) and hydrolysis (17%). This finding stresses once more the need for strong research efforts in the area of cellulase production.

Estimates for the ethanol yield from the forage crops included in this study are shown in Table 5. These estimates are based on a 45% ethanol yield from glucose during anaerobic fermentation. As expected, sudan grass and the brown midrib mutants of sorghum show the highest potential with respectively 276 and 250 gallons of EtOH/acre-year. The ensiled sorghum materials show the second best possibility with an ethonol yield close to 200 gallons/acre-year. Vegetative Frontier 214 sorghum and vegetative alfalfa rank at the bottom with respectively 109 and 97 gal/acre-year.

The estimated total production costs are shown in Table 6. These costs show that vegetative sudan grass 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 $1.68/gallon, with alfalfa and Frontier 214 sorghum reaching $2.58/gallon of 95% EtOH.

A breakdown of the total production costs presented in Table 6 can be seen in Table 7. It can be observed that substrate costs represent the major fraction of the total cost, ranging from a minimum of 34% to a maximum of 57%. Enzyme costs rank second, ranging from 23 to 35%, followed by fermentation and distillation costs which vary from 13 to 20% of the total. Hydrolysis costs represent the minor fraction, varying from 7 to 11% of the total production costs.

Table 8 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 6 is observed, reflecting the smaller quantity of forage raw materials required for the same ethanol production rate. The decrease averages about 10¢/gallon and reflects the high cost of the raw materials and the need for an efficient substrate conversion at all stages of the process.

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 ranged from $1.68/gallon for vegetative sudan grass to $2.58/gal. 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 byproducts credit; if proper account of these credits were observed, the costs reported in this study could be lowered by as much as 54¢/gallon. Since no pretreatment is required for the vegetative forage materials, processing costs are about 30% 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 34% to 57%. In view of this, an efficeint substrate conversion must be obtained at all stages of the process. Enzyme production costs were also very important, ranging from 23 to 35% of the total cost; this indicates the need for continued research on cellulase production technology.

The total capital investment for a 25 million gallons/year ethanol plant was found to be about 71 million dollars. This represents a fixed capital investment of about $2/gallon EtOH capacity.

In order to reduce substrate costs, one might either look for less expensive means of culturing and harvesting the crops or to coupling to other operations whereby the lignocellulosics obtain a discounted value. 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 zero to ten cents/gallon of ethanol product.

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 D.O.E. contract to A.D. Little Corporation and Jackson (20) at Battelle Columbus Laboratories screened herbaceous plants for potential biomass production in ten 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 (21). Sweet sorghum rated highest in that study, but in terms of practical energy recovery, cane storage, and juice expression present major difficulties at present (22).

Future crops for alcohol fermentation may include other traditional food crops, certain weeds, syrup sorghum, Jerusalem artichoke, and the 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. They 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). In order 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 relatively reduced when the biomass requires no pretreatment in order to obtain high percentage 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.

REFERENCES

1. Villet, R.H. 1979. Biotechnology for Producing Fuels and Chemicals from Biomass: Recommendations for R&D. Vol. I. SERI/TR-332-360. Golden, CO: Solar Energy Research Institute.
2. Emert, G.H. and R. Katzen, (1979). Chemicals from Biomass by Improved Enzyme Technology. ACS/CSJ Joint Chem. Congr. Hawaii.
3. Wang, D.I.C., I. Biocic, I., H.-Y. Fang and S.-D. Wang. 1979. Direct Microbiological Conversion of Cellulosic Biomass to Ethanol. Proc. DOE 3rd Ann. Biom. Energy Syst. Conf. p. 61.
4. Pye, E.K. and A.E. Humphrey. 1979. Production of Liquid Fuels from Cellulosic Biomass. Paper presented at the Third Annual Biomass Energy Systems Conference. DOE meeting, Golden, CO. June 5-7, p. 69.
5. Wilke, C.R., R.D. Yang, A.F. Sciamanna and R.P. Freitas. 1978. 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. D.O.R. meeting, Troy, New York. June 20-22.
6. Spano, L., A. Allen, T. Tassinari, M. Mandels and D.Y. Ruy. 1978. Reassessment of Economics of Cellulase Process Technology: For Production of Ethanol from Cellulose. Paper presented at the Second Annual Symposium on Fuels from Biomass. DOE meeting, Troy, New York. June 20-22.
7. Morrison, I.M. 1974. Strucutral Investigations on the Lignin-Carbohydrate complexes of *Lolium perenne*. Biochem. J. 139, 197-204.
8. Polein, J. and B. Bezuck. 1977. Investigation of enzymatic hydrolysis of lignified Cellulosic Materials. Wood Sci. Technol. 11:275-290.
9. Esau, K. 1953. Plant Anatomy, 2nd ed. John Wiley and Sons, N.Y.
10. White, G.A., T.F. Clark, J.P. Craigmiles, R.L. Mitchell, R.G. Robinson, E.L. Whiteley and K.H. Lessman. 1974. Agronomic and Chemical Evaluation of Selected Sorghums as Sources of Pulp. Economic Botany. 28:136-144.
11. Crookston, R.K., C.A. Fox, D.S. Hill and D.N. Moss. 1978. Agronomic Cropping for Maximum Biomass Production. Agronomy Journal. 70:899-902.
12. Schmidt, A.R., R.D. Goodrich, R.M. Jordan, G.C. Marten and J.C. Meiske. 1976. Relationships Among Agronomic Characteristics of Corn and Sorghum Cultivars and Silage Quality. Agronomy Journal. 68:403-406.
13. Lipinsky, E.S., S. Kresovitch, T.A. McClure and W.T. Lawhon. 1978. Fuels from Sugar Crops. Third Quarterly Report to U.S. DOE. TID-28191.
14. Leatherwood, J.M., R.E. Mochrie, E.J. Stone and W.E. Thomas. 1963. Cellulose Degradation by Enzymes Added to Ensiles Forages. J. Dairy Sci. 46:124-127.

15. Linden, J.C., W.S. Hedrick, A.R. Moreira, D.H. Smith and R.H. Villet. 1979. Enzymatic Hydrolysis of the Lignocellulosic Component from Vegetative Forage Crops. in Biotechnol. and Bioeng. Symposium No. 9. (in press)

16. Saterson, K.A. and M.K. Luppold. 1979. Herbaceous Species Screening Program - Phase I. DOE Contract ET-78-C-02-5035-A000.

17. Marshall & Stevens Equipment Cost Index. 1979. Chemical Engineering, 86(24), p. 7 November 5.

18. Goering, H.K. and P.S. Van Soest. 1970. Handbook No. 379. ARS-USDA. Washington, D.C.

19. Fritz, J.O., R.P. Cantrell, V.L. Lechtenberg, J.C. Axtel and J.M. Hertel. 1979. Fiber Composition and IVDMD of Three bmr Mutants in Grain and Grass Type Sorghums. Abstracts of Crop Science Society of America Annual Meetings. p. 128.

20. Jackson, D.R. 1979. Common Weeds and Grasses May Prove to be Valuable Sources of Energy. Biomass Digest 1 (no. 11):2.

21. Heichel, G.H. 1975. Energetics of Producing Agricultural Sources of Cellulose. Biotechnol. Bioeng. Symp. No. 5:43-47.

22. Lipinski, E.S., S. Kresovitch, T.S. McClure and W.T. Lawhon. 1978. Fuels from Sugar Crops. DOE Quarterly Report TIC-28191.

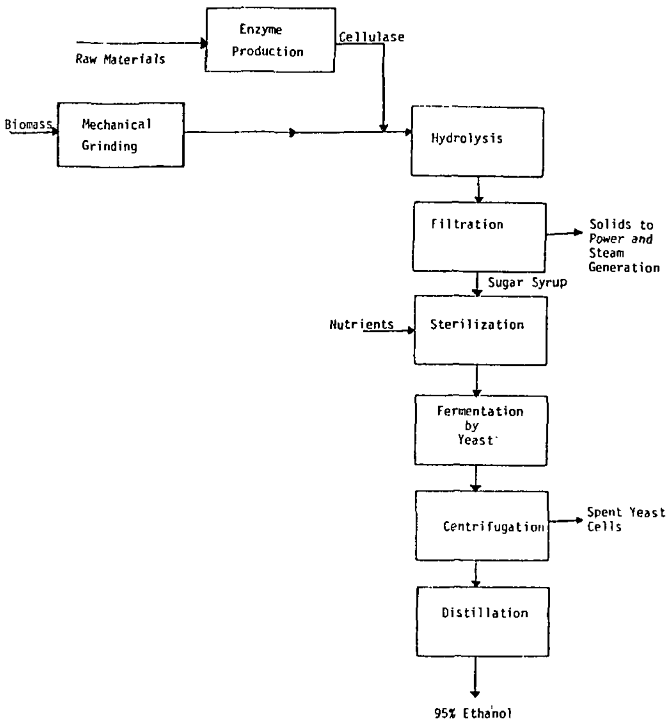

Figure 1. Simplified process flow diagram for ethanol production from vegetative forage crops.

Table 1. 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/gm dry substrate - day			percent
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
Sudan Grass				
vegetative	204	64	140	56
Brown Midrib Mutants of Sorghum				
vegetative, fieldgrown				
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 (1st cutting, vegetative)				
top	NA			
next-to-top	NA			
next-to-bottom	NA			
bottom	128	5	123	43
Alfalfa (2nd 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 2 and multiplying by 100.

Table 2. Fiber composition of forage sorghum varieties as percent on dry weight basis.[a]

	cell soluble material	acid detergent fiber	hemi-cellulose	cellulose	lignin
Dekalb FS-25A+					
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					
vegetative	44.2	38.8	17.0	30.3	3.9
silage	45.1	35.3	19.5	25.9	4.5
Sudan Grass					
vegetative	45.6	29.7	24.7	25.2	3.1
Brown Midrib Mutants					
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 (1st 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 (2nd 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 (17).

Table 3. Estimated Capital Investment for a 25 x 10^6 Gallons/Year Ethanol Plant (U.S. $1,000, Third Quarter 1979)

	Enzyme Production	Hydrolysis	Ethanol Production	Total
Major Equipment	17,243	13,350	15,186	45,779
Off-Site Investment	1,869	108	4,242	6,219
General Service Facilities	1,911	1,346	1,943	5,200
Total Fixed Investment	21,023	14,804	21,371	57,198
Start-Up (8.5% TFI)				4,862
Working Capital (16.5% TFI)				9,438
Total Capital Investment				71,498

Table 4. Cost Analysis, Ethanol from Cellulose*

	Enzyme Production	Hydrolysis	Ethanol Fermentation and Distillation	Total
Total Material	33.60	1.31	1.92	36.83
Total Utilities	5.93	4.54	11.96	22.43
Total Direct Labor	5.19	3.11	4.90	13.20
Total Direct Cost	44.72	8.96	18.78	72.46
Plant Overhead	4.15	2.49	3.92	10.56
Tax and Insurance	1.68	1.18	1.71	4.57
Depreciation	8.41	5.92	8.55	22.88
Factory Cost	58.96	18.55	32.96	110.47
% Total Cost	53	17	30	100

*Basis: cents/gallon, 95% ethanol, no substrate charge

Table 5. Estimated Ethanol Yields from Several Forage Materials*

Raw Materials	Total glucose yield $\left(\frac{\text{kg glucose}}{\text{MT dry substrate-day}}\right)$	Substrate yield (MT/ha-yr)	Ethanol Yield $\left(\frac{\text{liters}}{\text{ha - yr}}\right)$	Ethanol Yield $\left(\frac{\text{gallons}}{\text{acre-yr}}\right)$
Dekalb FS-25A+				
vegetative	155	17.3	1530	164
mature	151	17.3	1490	159
silage	188	17.3	1855	198
Frontier 214				
vegetative	103	17.3	1016	109
silage	175	17.3	1727	185
Sudan Grass				
vegetative	204	22.2	2583	276
Brown Midrib Mutants of Sorghum				
vegetative (average)	237	17.3	2338	250
Alfalfa				
vegetative (average)	120	13.2	903	97

*Basis: ethanol yield during glucose fermentation = 45% on a weight basis

Table 6. Estimated Total Ethanol Production Costs from Several Forage Materials*

Raw Materials	Substrate Cost ($/MT)	Substrate Charge to EtOH Cost ($/gal 95% EtOH)	Total EtOH Production Cost ($/gal 95% EtOH)
Dekalb FS-25A+			
vegetative	22.71	0.97	2.07
mature	22.71	1.00	2.10
silage	22.71	0.80	1.90
Frontier 214			
vegetative	22.71	1.46	2.56
silage	22.71	0.86	1.96
Sudan Grass			
vegetative	17.75	0.58	1.68
Brown Midrib Mutants of Sorghum			
vegetative (average)	22.71	0.64	1.74
Alfalfa			
vegetative (average)	26.78	1.48	2.58

*Ethanol processing costs = 110.47¢/gallon (from Table 4)
Ethanol yield during glucose fermentation = 45% on a weight basis

Table 7. Relative Cost Factor Analysis of Ethanol Production Costs from Several Forage Materials

Raw Materials	Substrate Cost (% Total)	Enzyme Production Cost (% Total)	Hydrolysis Cost (% Total)	Fermentation and Distillation Cost (% Total)
Dekalb FS-25A+				
vegetative	47	28	9	16
mature	48	28	9	16
silage	42	31	10	17
Frontier 214				
vegetative	57	23	7	13
silage	44	30	9	17
Sudan Grass				
vegetative	34	35	11	20
Brown Midrib Mutants of Sorghum				
vegetative (average)	37	34	11	19
Alfalfa				
vegetative (average)	57	23	7	13

Table 8. Estimated Total Ethanol Production Costs from Several Forage Materials*

Raw Materials	Substrate Charge to EtOH Cost ($/gal 95% EtOH)	Total EtOH Production Cost ($/gal 95% EtOH)
Dekalb FS-25A+		
vegetative	0.87	1.97
mature	0.90	2.00
silage	0.72	1.82
Frontier 214		
vegetative	1.32	2.42
silage	0.77	1.87
Sudan Grass		
vegetative	0.52	1.62
Brown Midrib Mutants of Sorghum		
vegetative (average)	0.57	1.67
Alfalfa		
vegetative (average)	1.33	2.43

*Ethanol processing costs = 110.47 ¢/gallon (from Table 4)
Ethanol yield during glucose fermentation = 50% on a weight basis.