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Sweet Sorghum Grown on Sludge-Amended Stripmine Soil: A Preliminary Look at Yields, Composition, and Ethanol Production

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*The mention of firm names or trade products does not imply that they are endorsed or recommended by the U.S. Department of Agriculture over other firms or similar products not mentioned.

ABSTRACT

Results of a one-year field plot study are reported for sweet sorghum [*Sorghum bicolor* (Moench), variety Wray] grown on stripmine soil in three replications of four soil treatments: control (no amendment); commercial fertilizer; and two levels of sewage sludge amendment (209 and 418 t/ha total dry solids, respectively). Mean sucrose content of whole-stalk dry solids was 35%. Juice yields of 50-68% from fresh stalks were obtained, and the 14% total sugar concentration in the juice was readily fermented by *Saccharomyces cerevisiae* to ethanol in 72% yield. Since sucrose content of the bagasse dry solids was 24%, additional fermentable substrate can be obtained by water extraction. Without additional pretreatment, about 13% of the cellulose in the fresh bagasse was converted to glucose by standard cellulase treatment. More detailed studies are underway on using stripmine land and sewage sludge to produce sweet sorghum as a possible feedstock for fuels and chemicals.

INTRODUCTION

The principal carbohydrates of plant tissues serve as structural components (cellulose and hemicellulose), but large amounts of readily metabolizable carbohydrates (starch and sucrose) may be stored in plants to serve as energy sources (Goldstein, 1981). A major effort has been launched to obtain fermentable sugars from biomass for production of liquid fuels and chemicals. To prepare lignocellulosics

for such conversion, pretreatment processes are being explored that destroy fiber structure and disrupt the lignin-hemicellulose-cellulose complex (Lipinsky, 1979).

Sweet sorghums are varieties of *Sorghum bicolor* (Moench) that accumulate considerable sugar (mainly sucrose) in their stalks during maturation. Although it has been grown for syrup and forage production, sweet sorghum has many attributes as an energy crop based on direct conversion of extracted sugar to ethanol and on energy and chemical production from the associated biomass (Nathan, 1978). With succulent stems, relatively low grain yields, and stalk lengths of 1.8 to 4.3 m, sweet sorghums provide an interesting comparison with commercial hybrid grain sorghums that have drier stems, high grain yields, and attain uniform heights of only 0.9 to 1.2 m (Owen and Moline, 1970). However, as new sweet sorghum varieties are developed for higher sugar yields, grain and biomass yields will become important also in overall economic considerations. Sweet sorghum has appeal as an energy crop because it exhibits great genetic diversity that promises wide adaptability to geographic and climatic conditions, soil types, fertilizer and water requirements, and overall agronomic practices (Nathan, 1978; Coleman, 1970; Jackson and Arthur, 1980; Jackson and Lawhon, 1981).

Recent studies at our Center have shown that crambe and kenaf can be grown on stripmine soil amended with sewage sludge (Carlson *et al.*, 1982). These potential industrial crops — crambe as an oilseed source of erucic acid for production of erucamide (slip and anti-block additive for polyethylene films), and kenaf as a fiber source for newsprint and other types of paper — do not directly involve the food chain. Without diverting current food production acreage, the use of stripmine land and sewage sludge to economically produce sweet sorghum as a feedstock for fuels and chemicals also is conceptually attractive. Both USDA and the Metropolitan Sanitary District of Greater Chicago (MSDGC), cooperator on our most recent work with crambe and kenaf, are interested in energy-from-biomass research programs. In our studies with MSDGC we have observed that sludge amendment of stripmine soils can promote earlier emergence of seedlings from the soil, but that overall germination, emergence, and seedling survival rates may be lower. We have also encountered severe competition by barnyard grass, *Echinochloa crusgalli*, on sludge-treated plots, but we now feel this can be controlled in crambe and kenaf with timely application of postemergence herbicides such as Hoelon®. In practice, seeding rates can be adjusted to give proper plant densities on the amended soils, but grass problems are likely to be more difficult to control chemically with a crop of the Gramineae family (grass) like sweet sorghum.

Our established kenaf plots, which had received annual applications of sludge over a three-year period, provided an immediate opportunity to observe sweet sorghum grown on sludge-treated stripmine soils, thus alerting us to potential problems affecting performance that might be associated with sludge amendment. Pot trials in an environmental growth chamber with sludge-amended soils from the field suggested that soil constituents could affect germination of seeds and development of seedlings. Although preliminary in design, these studies served as valuable indicators of sweet sorghum's likely performance as we planned for more extensive field trials.

We report here the results of our one-year study of sweet sorghum grown in three replications of four treatments: control (C, no amendment); commercial fertilizer (CF); and two levels of sewage sludge amendment (S-209 and S-418). Reported are millable stalk, sugar, and juice yields, whole stalk and bagasse com-

positional data, and evaluations of the expressed juice and bagasse as fermentable substrates.

MATERIALS AND METHODS

Twin sets of experimental plots on stripmine soil on MSDGC property in Fulton County, IL, were first established in 1979 for a three-year study with crambe and kenaf. Each set consisted of 12 plots measuring 15 m × 15 m in a randomized complete block design arranged in a linear array approximately 198 m long and providing 3 replications of 4 soil treatments. In 1981, a 3 m × 198 m strip within and along the south side of the kenaf array provided twelve 3 m × 15 m sorghum plots sharing the soil treatments of the contiguous kenaf plots (east-west rows, 2 m separated sorghum and kenaf).

The plot area was worked to depths in excess of 30 cm in 1979 with equipment designed to pulverize blacktop roadways and rocks. Anaerobically digested sludge (ca. 5% solids) from MSDGC's West-Southwest Sewage Treatment Works was lagooned at the Fulton County site for use in the District's reclamation operations. Sludge solids, later removed from the emptied lagoon, were used in our studies and were 50-69% dry solids when applied by manure spreader to appropriate low- or high-level sludge plots annually at rates of 112 t/ha (S-209) and 224 t/ha (S-418), respectively. Thus, total sludge dry solids applied between 1978 and 1981, and prior to planting the sorghum, were 209 t/ha and 418 t/ha, respectively. Commercial fertilizer, mixed to give 112N/67P/67K kg/ha, was broadcast annually on the appropriate CF plots. Control plots received no amendment except, along with all other plots, an application of potash at the annual rate of 112 kg/ha to counter a generally low K level in the stripmine soil. Annually, prior to seeding and after amendments had been applied, the plots were disced 2 or 3 times crosswise to incorporate sludge and 2 or 3 times lengthwise (long axis of plot area) to further incorporate sludge and plant residues and to prepare the seed bed for planting. Trenches, 0.5 m deep × 1.5 m wide, were cut between plots each year after seeding. Weeds were partly controlled with annual preplant applications of Treflan®at 1.12 kg/ha and by cultivation, but no herbicide was applied to the sorghum strip in 1981.

A single row of sweet sorghum (*S. bicolor*, variety Wray) was planted in the 3 m × 198 m strip on June 1, 1981, with a hand-operated Planet Jr. seeder set to drop seeds at 10-15 cm intervals and a depth of 2.5-5 cm. All plots were cultivated on June 29 to eliminate competing weeds, especially barnyard grass, in sludge-treated plots. Harvest by hand cutting occurred on October 5, 1981, 127 days after planting. Three representative stalks (short, medium, long) were collected from each of the 12 plots, and the replicated samples (9 stalks/treatment, 36 stalks total) were combined to provide composited material for analyses (total representative harvest was 45 kg). Additionally, all stalks were harvested from plots 1-6 (99 m of row), which provided another 378 kg of fresh stalks for a yield estimate and material for storage studies being conducted in another program at the Center. Approximately 60-90 cm of upper stalk and seed head as well as leaves and sheaths were left in the field.

Stalks for expression of juice were sectioned into 5-7.5 cm lengths. Juice was extracted in a slotted, cylindrical, hydraulic press (8.7 cm diam. × 15 cm length) pressurized 3 to 5 times to 1,054 kg/cm^2 (3 or 5 × to 15,000 psig), each time allow-

ing the pressure to drop to 703 kg/cm^2 (10,000 psig). Portions of bagasse from these pressings were repressed similarly to establish maximum juice yields. Juice and bagasse were weighed and immediately frozen until needed.

Chemical composition was determined on sectioned whole stalk or bagasse samples after they were freeze-dried and ground to pass a 1-mm screen in a Wiley mill. Cellulose content was determined by the monoethanolamine (MEA) method (Nelson and Leming, 1957) and reported on an ash- and pentosan-free basis. Lignin analyses were made by the spectrophotometric method (Bagby *et al.*, 1973). Nitrogen was determined by the Kjeldahl method (AOAC, 1980). Water extracts of the freeze-dried and ground whole stalk or bagasse samples were analyzed for soluble sugars by high-performance liquid chromatography (HPLC) with a BioRad (Richmond, CA) HPX-87H size exclusion column and water as the mobile phase. Other analytical procedures were standards of the Technical Association of the Pulp and Paper Industry.

Fermentability of the expressed juice was evaluated as follows: Sterile 60 ml stoppered glass pyrex test tubes containing 17 ml of sorghum juice and 3 ml of Del Rosaria medium (Del Rosario, 1979) were inoculated with 0.1 ml of 24-hr culture of *Saccharomyces cerevisiae* NRRL Y2034. Initial cell counts were 7.0×10^5/ml and the pH was 4.5. Tubes were incubated at 22 C. Over 3 days, 2-ml aliquots were taken at 24-hr intervals for cell counts (haemocytometer) and for determination of glucose/fructose, sucrose, and ethanol concentrations. Sugar analyses were run by HPLC with a 3.9 mm × 30 cm Waters carbohydrate analysis column (Waters Associates, Inc., Milford, MA) and acetonitrile-water (75:25) as mobile phase. Glucose and fructose were not resolved with our procedure. Ethanol concentrations were determined by gas-liquid chromatography.

Thin-layer chromatography (TLC) was performed on commercial precoated plates (0.25 mm silica gel 60 F-254, E. Merck, Darmstadt, Germany). Developing solvent was ethyl acetate:*n*-propanol:methanol:water (55:15:20:7.5) or ethyl acetate:methanol:water (55:40:7.5). Visualization was by charring at 130 C with sulfuric:chromic acid solution or, for colored spot visualization, by heating at 100 C for 10 min after spraying with a fresh solution of ethanol:sulfuric acid:anisaldehyde (9:0.5:0.5) (Waldi, 1965).

Convertibility of cellulose to glucose in sectioned fresh stalks and once-pressed (3 X to 15,000 psig) fresh bagasse was tested by a standard cellulase treatment (Detroy *et al.*, 1980). Thus, 2 to 3.6 g of sectioned fresh stalk material (mean dry solids 28.3%) or 0.9 to 2.7 g of freshly pressed bagasse (49.3% mean yield, 39.3% mean dry solids), representing each of the four soil treatments, were treated for 18 hours with cellulase in a buffered working volume of 20 ml. Comparable buffered samples treated identically, but without cellulase, served as controls. Glucose and sucrose concentrations, for calculating cellulose conversion, were determined on filtrate aliquots by HPLC.

RESULTS AND DISCUSSION

Sweet sorghum yield data are shown in Table 1. Stalk lenghts and diameters ranged from 2.4 to 3.7 m and 2.5 to 5 cm, respectively, with good upright stature. The shorter stalks generally resulted from intense grass competition prior to cultivation, and were mainly in the high-level sludge plots. With an average of 3.42 stalks/m of row and mean weights of 1.25 kg/stalk, each meter of row produced

4.27 kg of fresh stalk after leaves, seed heads, and 60-90 cm of upper stalk had been removed. Total harvest of millable stalks from 99 m of row was 423 kg, which extrapolates to ca. 56 t/ha. Differences due to soil treatments for all parameters in Table 1 are small, with relative standard deviations (RSD) from the means of less than 10%. Yields of juice expressed from fresh stalks with a small roll-type farm mill were comparable to those in the laboratory pressings (ca. 50%) as shown in Table 1. Using the laboratory press, juice yield was increased to 60% by pressing at 5 X to 15,000 psig, and to 68% by re-pressing the bagasse at 5 X to 15,000 psig.

Stalk quarters contributed the following weight percentages to the fresh weight: top quarter, 6%; upper middle quarter, 14%; lower middle quarter, 27%; bottom quarter, 49%; and associated sheaths, 4%. As harvested in this study, the bottom three quarters thus represent 90% of the fresh weight and at least that proportion of juice. Separate pressings of the quarters (at 5 X to 15,000 psig) gave juice yields in the range of 55 to 66% for the three lower quarters, and only 52% for the top quarter. TLC analyses of the separate juice fractions showed no gross differences in the juice sugars, largely sucrose with small quantities of glucose/fructose (not separated). After repressing the combined recovered bagasse, more glucose/fructose was apparent in this juice, suggesting that sucrase action may occur sometime after stalks are initially crushed.

We tested the feasibility of converting cellulose in the fresh sorghum samples by incubating them with a standard cellulase preparation followed by glucose analyses on the resulting reaction media. We found that estimates of cellulose conversion on sectioned fresh stalks were extremely variable and too unreliable for further consideration [mean 5.83% (RSD 242%)]. In contrast, Table 2 shows that cellulase action on the several fresh bagasse samples was very uniform, with a mean cellulose conversion of 13.2% (RSD 6.85%). Cellulosic conversions of 10 to 20% are reasonable for plant material receiving no more pretreatment or size reduction than the bagasse received. To estimate the extent of conversion, glucose initially present in the substrates was subtracted from the glucose levels after cellulase treatment. Furthermore, sucrose levels decreased relative to the buffered controls as a result of cellulase treatment. We assumed that sucrase activity was responsible, and we corrected glucose concentrations accordingly on the basis of 1 g sucrose yields 1.053 g of glucose/fructose (not separately determined). Our conversion estimates in Table 2 will be minimum values if some other process that doesn't generate glucose is responsible for the sucrose disappearance, e.g., a fermentation process. However, we would expect such a process to diminish sucrose levels equally in both the buffered controls and the cellulase-treated samples, and therefore, a differential decrease in sucrose concentration would not have been apparent. Our experience suggests that in using standard cellulase preparations and procedures, it may be necessary to consider that glucose can be generated from substrates other than cellulose, sucrose in our case, and that cellulose conversions could be erroneously high if corrections are not made in these instances.

Fermentability of the sweet sorghum juices was tested in standard incubations with *S. cerevisiae*. Table 3 shows the initial sugar concentrations of juices pressed at 3 X to 15,000 psig, 72-hour fermentation ethanol yields, and the maximum cell counts attained after 48 hours of fermentation. Ethanol yields ranged from 67 to 75% of theory with a mean of 72% (RSD 5.27%) based on initial total sugar concentrations. Mean ethanol concentrations in the fermented juices reached 5.5%

(RSD 4.63%) after 72 hr. We have no information to account for the sugar not converted to ethanol.

Cell populations doubled 6 to 8 times during the fermentations, reaching maxima at 48 hours and declining thereafter (Table 3; Fig. 1). A difference of one generation of cells can account for the apparent population differences by treatment (C S-418 CF~S-209).

Utilization of sucrose and production of ethanol during fermentation are shown as functions of time in Fig. 2. Apparent "induction periods" for sucrose utilization and slightly higher ethanol yields are associated with the control and S-418 juices. These same juices are associated with what may be higher cell populations at 48 or 72 hours (Fig. 1). Since all juices contained similar concentrations of glucose/fructose, which initially would have been used preferentially by the yeast, "induction periods" for sucrose utilization might have been expected for all four juices. However, since these experiments were not replicated, the significance, if any, of the apparent differences in cell populations, sucrose utilization rates, and ethanol yields is not clear at this time.

Compositional data for freeze-dried sectioned whole stalks and once-pressed bagasse are shown in Table 4. The mean sucrose contents (water extractable) of these materials were 35.4% (RSD 18.4%) and 24.3% (RSD 8.2%), respectively. From these data and dry solids contents, fresh stalks as harvested contained at least 9.5-10% sucrose, of which at least 63% is removed in the first-press juice (% juice yield X % sucrose).

Total nitrogen contents of stalks grown on the amended soils are about double the nitrogen content of stalks grown on the control plots. After juice extraction, the nitrogen levels of bagasse from all treatments are similar, suggesting that a soluble form of nitrogen is removed with the juice and is responsible for the higher levels in whole stalks from the fertilized plots.

Alcohol-benzene solubles in the freeze-dried materials ranged from 15 to 35%, or about 4 to 10% on a whole fresh stalk basis, and measures waxes, lipids, and other organics extracted by the hot azeotrope (95% ethanol/benzene, 1:2 v/v). The high sugar content and early stage of maturity may be contributing factors in these relatively high extract levels. Ash levels appear to be somewhat higher in stalks from amended plots as a result of added minerals from the fertilizer and sludge.

Cellulose by monoethanolamine (MEA) extraction ranged from 17 to 20% of the freeze-dried whole stalks and 23 to 26% of the corresponding bagasse. Alpha cellulose values were ca. 1 to 2% lower. Lignin contents of the stalk and bagasse tend to parallel the cellulose and pentosan contents. The pentosan levels in the sorghum bagasse were similar (20-23%), as were the whole stalk levels (15-16%) with the exception of stalks from the CF plots. With the recent finding that the yeast *Pachysolen tannophilus* is capable of direct fermentation of xylose to ethanol (Schneider *et al.*, 1981; Slininger *et al.*, 1982; Detroy *et al.*, 1982a, 1982b), the amount of pentosans (and thus xylose) present in sorghum bagasse is of some significance. In general, pentosans are hydrolyzed under milder reaction conditions than used for cellulose hydrolysis and the remaining residue then is more susceptible to cellulose hydrolysis by enzymes or acid (Lee *et al.*, 1978). Theoretically, xylose from pentosans could be fermented to ethanol by *P. tannophilus*, and glucose, hydrolyzed from the cellulosic residue, could be fermented to ethanol by

S. uvarum (Detroy *et al.*, 1982a) to add to the ethanol obtained from sucrose fermentation.

In summary, with the exception of the need for vigorous grass control measures on sludge-treated soils, we encountered no obvious problems in growing sweet sorghum on stripmine soils. No other negative factors associated with sludge treatment were apparent. Although preliminary, our study serves as a useful indicator of sweet sorghum's performance when grown under these conditions, and the results have proved useful in designing more complete experiments. The data reported should be interpreted within the context of limitations in experimental design and one-year term of the study. Juice yields of 50-68% from fresh stalks were obtained, and the 14% total sugar in the juice was readily fermented by *S. cerevisiae* to ethanol in 72% yield. Since sucrose content of the bagasse dry solids averaged 24%, additional fermentable substrate should be available by water extraction. Moreover, without additional pretreatment, about 13% of the cellulose in the fresh bagasse was converted to glucose by standard cellulase treatment. Approximately 20% and 25%, respectively, of the bagasse dry solids are pentosans and cellulose, which if hydrolyzed would provide additional fermentable substrates.

Based on our results, Fig. 3 provides an estimate of the quantity of ethanol theoretically produced by fermentation of readily extracted sucrose in the sweet sorghum grown in our experiment. Nearly 500 gal (1862 L/ha) is indicated by direct fermentation of the sugar in the expressed juice, and another 300 gal (1200 L/ha) is estimated from fermentation of sucrose that can be washed from the bagasse. Alternatively, sucrose washed from whole stalk dry solids would yield nearly 700 gal/ha (2550 L/ha). All these estimates are based on 72% fermentation yield of ethanol as observed in the direct juice fermentation.

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Table 1. Yields of sweet sorghum grown on stripmine soils.

Soil treatment	Fresh stalks* Yield, kg	Fresh stalks* Dry solids, %	Juice† Yield, %	Bagasse† Yield, %	Bagasse† Dry solids, %
Control (C) (No Amendment)	10.9	28.1	51.1	48.9	37.6
Comm. fertilizer (CF) (112N/67P/67K, kg/ha)	12.8	27.9	53.1	46.9	38.6
Sewage sludge (S-209) (209 t/ha dry solids)	11.0	27.7	48.4	51.6	40.5
Sewage sludge (S-418) (418 t/ha dry solids)	10.3	29.5	50.2	49.8	40.3
Mean	11.2	28.3	50.7	49.3	39.3
(RSD)‡	(9.52)	(2.97)	(3.85)	(3.96)	(3.55)

*Yield is total weight of 9 stalks, 3 harvested from each replicate to form the treatment composite.

†Single pressing of fresh stalks at 3 X to 15,000 psig.

‡Relative standard deviation, %.

Table 2. Cellulase treatment of sweet sorghum bagasse.*

Soil treatment	Concentrations, g-%/g substrate: Sucrose, Net Decrease†	Glucose: Gross Increase‡	Glucose: Sucrose Equivalent§	Glucose: Net Increase¶	Cellulose Conversion,# %
Control (C) (No Amendment)	- 0.38	0.59	0.40	0.19	14.6
Comm. fertilizer (CF) (112N/67P/67K, kg/ha)	- 0.40	0.58	0.42	0.16	12.5
Sewage sludge (S-209) (209 t/ha dry solids)	- 0.12	0.31	0.13	0.18	12.5
Sewage sludge (S-418) (418 t/ha dry solids)	- 0.61	0.81	0.64	0.17	12.6
Mean	- 0.38	0.57	0.40	0.18	13.2
(RSD)	(52.9)	(35.6)	(52.9)	(6.11)	(6.85)

*Mean bagasse yield from fresh whole stalks was 49.3% (RSD 3.96%), and the mean dry solids was 39.3% (RSD 3.55%). Cellulase treatment of fresh bagasse (0.92-2.24 g wet, or 0.37-0.86 g dry solids) according to Detroy et al. (16) with buffered controls. RSD = relative standard deviation, %.

$$\#\% \text{ conversion} = \frac{\text{Net glucose X 0.9 X 20}}{\text{MEA cellulose (\%)}} \text{ X 100.}$$

†Sucrose levels decreased with cellulase treatment, relative to buffered controls.

‡Difference between cellulase treated samples and buffered control samples.

§Calculated quantity of glucose and fructose (not separated) assumed to be formed from sucrose that disappears during the reaction. Glucose + fructose (MW = 360) /sucrose (MW = 342) = 1.053 X decrease in sucrose concentration.

¶Column 3 minus column 4.

Table 3. Fermentation of sweet sorghum juice from plants grown on stripmine soil.*

Soil treatment	Initial concentration of juice sugars			Concentration of ethanol produced		Maximum cell count, 48 hour
	Glucose-Fructose,† %	Sucrose, %	Total, %	Final, %	% of Theory‡	X 10^{-5}/ml
Control (C) (No Amendment)	2.23	11.8	14.0	5.63	74.7	1500
Comm. fertilizer (CF) (112N/67P/67K, kg/ha)	2.05	12.7	14.7	5.30	67.0	700
Sewage sludge (S-209) (209 t/ha dry solids)	1.83	12.4	14.3	5.37	69.9	800
Sewage sludge (S-418) (418 t/ha dry solids)	2.07	12.5	14.6	5.86	74.6	800
Means	2.05	12.4	14.4	5.54	71.6	950
(RSD)§	(8.04)	(3.12)	(2.20)	(4.63)	(5.27)	(38.9)

*Juices from a single pressing at 3 X to 15,000 psig, mean yield from fresh stalks = 50.7% (RSD 3.85%).

†Not separated by analytical technique, assumed to be a mixture.

‡Based on total initial sugar concentration.

§Relative standard deviation, %.

Table 4. Chemical composition of sweet sorghum grown on stripmine soil.*

Soil treatment	Chemical composition†							
	Solubility in Alcohol-Benzene, %	Cellulose by MEA, %	Cellulose Alpha %	Pentosans %	Lignin %	Ash %	Nitrogen %	Sucrose %
Control (C)	25.1	17.0	15.6	15.2	16.1	2.57	0.26	37.5
(No Amendment)	(30.4)	(23.5)	(21.4)	(22.7)	(9.0)	(2.52)	(0.42)	(24.5)
Commerical fertilizer (CF)	25.2	16.7	16.0	8.9	16.7	3.26	0.65	43.2
(112N/67P/67K, kg/ha)	(29.2)	(23.1)	(21.7)	(20.1)	(10.9)	(2.74)	(0.55)	(26.9)
Sewage sludge (S-209)	35.0	17.8	16.9	16.2	12.2	2.63	0.50	28.0
(209 t/ha dry solids)	(24.2)	(25.9)	(24.1)	(20.6)	(11.3)	(2.68)	(0.39)	(24.0)
Sewage sludge (S-418)	15.2	19.9	18.5	16.3	19.9	2.68	0.56	32.8
(418 t/ha dry solids)	(20.0)	(24.3)	(22.7)	(20.4)	(19.2)	(2.64)	(0.53)	(22.0)

*Analyses on freeze-dried material ground to pass 1 mm screen. Values in ( ) are for bagasse.

†Mean dry solids of whole fresh stalks and bagasse were 28.3% (RSD 2.97%) and 39.3% (RSD 3.55%), respectively. Mean bagasse yield was 49.3% (RSD 3.96%). RSD = relative standard deviation, %.

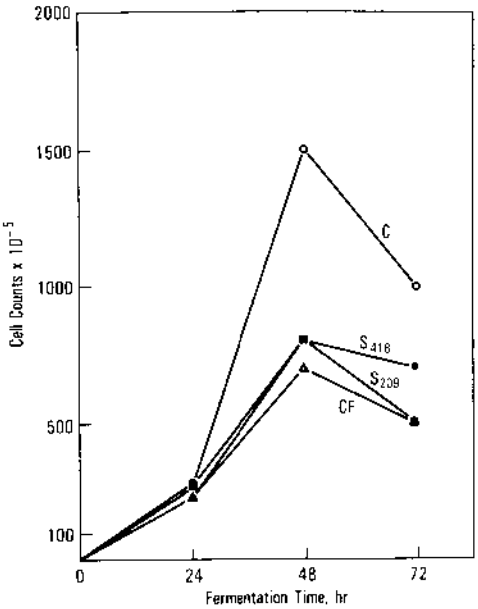

Fig. 1. Fermentation of sweet sorghum juice: Cell counts as a function of time and plot treatment.

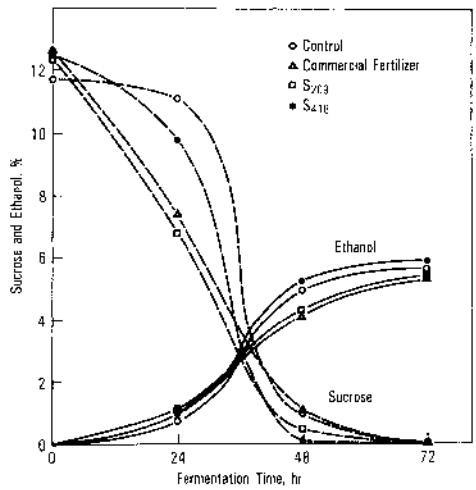

Fig. 2. Fermentation of sweet sorghum juice: sucrose utilization and ethanol production as a function of time and plot treatment.

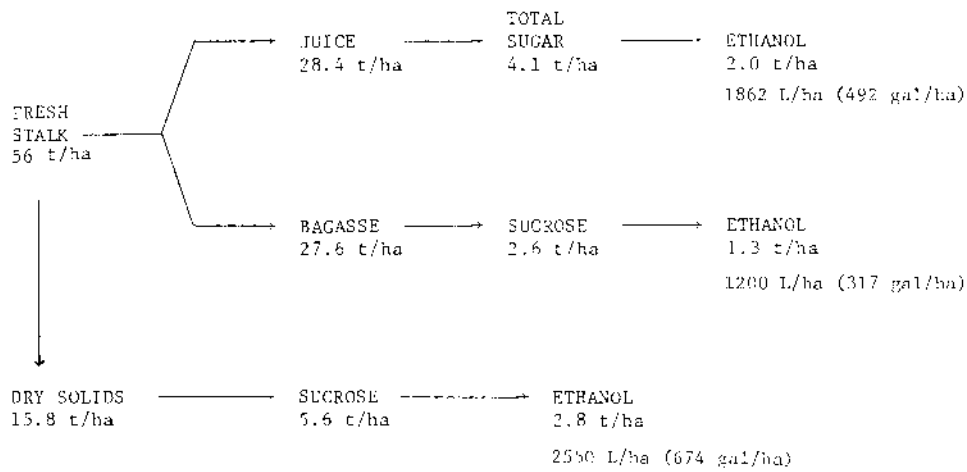

Fig. 3. Theoretical ethanol yields from total juice sugars, and from sucrose obtained from sweet sorghum bagasse or whole stalk solids.