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AGRICULTURAL AND HIGH STRENGTH WASTES

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INTRODUCTION

Anaerobic fermentation has been thought to be limited to wet organics such as sewage sludge that contain greater than 90 percent water. The processing of drier biomass at these high water contents requires the addition of many tons of water for every dry ton of biomass. Crop residues are particularly troublesome since they not only require large amounts of water, but are extremely difficult to handle. One approach to fermentation of the agricultural residues has been to develop a method that could ferment the material without the addition of large quantities of water. "Dry fermentation"* has been a topic of study at Cornell University since 1976 (Jewell et al., 1978), and it is presently the focus of a large-scale research effort. This paper provides a brief overview of this new concept.

BACKGROUND

Most biomass presently available for use in energy production is terrestrial biomass that exists in a relatively dry state. Cereal straw and cornstalks are representative materials, millions of tons of which are annually left in the field after the grain is harvested in the U.S. The moisture content may be as low as 15 percent of the total weight for much of this material, and lower than 50 percent for almost all of it. Where the residue is used for animal bedding, the resulting mixtures of manure and crop residue have a variable, but relatively low, moisture content.

Conventional anaerobic methane fermentation of crop residues or mixtures of animal wastes and crop residues require extensive preparation (chopping, water addition, mixing). They are difficult to control in the fermentor, and

*Defined as the organic solids content that do not have free water in void spaces or drainable water. Most organics above 15 percent dry solids exist in this form.

present many difficulties in final disposition of the digested effluent. An approach that could use crop residues in their dry "as produced" state could greatly simplify the conversion process. The dry fermentation process is being developed for this reason.

The question of the role of water in microbial methane production began to be examined in the Cornell methane project in 1976 (Jewell, et al., 1978). Surprisingly, it was found that relatively dry mixtures of organics could be efficiently converted to methane. Wujcik (1980) subsequently conducted comprehensive tests and found that at a moisture level as low as 68 percent of the total weight both the rate and the efficiency of biodegradable organic matter conversion was relatively unaffected. Decreasing the water content from 68 to 60 percent of the total weight caused methane formation to cease and volatile acids to accumulate at concentrations greater than 30 grams per liter. The hydrolysis of solid organics was shown to proceed at a moisture content above 40 percent.

The dry fermentation of crop residues appeared to simplify and enhance the possibilities for using crop residues as an energy source. Infrequent loading of the system and the relatively dry effluent residue showed that small units for residential use, farm scale, as well as large, community-size systems were potentially feasible. Further, on-farm use of the system provided a four- to tenfold increase in energy production potential over that available in animal manures, while the plant nutrients would be efficiently immobilized for future fertilizer use. The potential advantages and disadvantages of the dry fermentation concept are given in Table 1.

Hypothesized dry fermentation system

Until recently the possibility of using dry or solid substrates in the fermentation process has been limited to aerobic composting and food fermentations such as cheese production. In a recent review, Cannel and Moo-Young (1980a, 1980b) noted that few bacteria function at high solids. Production of gas in landfills is a well known phenomenon and is receiving increased attention, but it is still poorly defined.

Initially, production of methane from dry wheat straw appeared to be an interesting but impractical phenomenon. Further analysis has shown that this concept may have significant potential for systems of widely varying sizes. Further analysis has shown that, if the biochemical reaction rates can be increased to values near or equal to those achieved by conventional wet systems, the technology should be highly competitive with any known methane-producing system for the concentrated agricultural residues.

TABLE I

SUMMARY OF ADVANTAGES AND DISADVANTAGES OF USING A DRY REACTOR APPROACH FOR THE CONVERSION OF AGRICULTURAL CROPS AND RESIDUES TO METHANE

Advantages	Disadvantages
1. Minimizes handling and pretreatment requirements of agricultural products using in-place production and collection techniques.	1. Large reactor required.
2. Exceptionally simple design and operation.	2. Two large storage areas required for liquid or wet residues.
3. Low labor requirements.	3. Process limitations are poorly defined.
4. Indiscriminate in type of organic input that could be used.	
5. Little or no water requirement.	
6. Potential energy production could satisfy up to 100 percent of the total energy needs for many communities.	
7. Appears to be a self-sustaining reaction, which further simplifies the reactor design.	
8. Has major pollution control side benefits--eliminates liquid waste on farms and from cities, and uses a low nutrient feed which could result in control of highly volatile nitrogen products while producing a slow-release organic fertilizer as an end product.	
9. Appears to be capable of producing a final organic residue with moisture less than 50 percent.	
10. Overall economics are encouraging.	

It is assumed that batch reactors are required for a dry system, as compared to continuous feed methods. This is primarily related to the assumption that field collection, transport and storage methods for crops and crop residues will be similar to that presently in use and that minimum handling and no residue pretreatment are main goals of this design. Thus, once or twice per year loading of the batch reactor will be assumed to minimize labor requirements and residue handling and pretreatment needs. The long-term batch feed approach is also related to the assumption that the kinetics of decay for the untreated residues will be relatively low and require total reaction periods of 100 to 300 days duration before high efficiencies of biodegradable organic carbon conversions are achieved. Note that due to the higher densities of organics, a reactor volumetric production rate of 1 v/v/d of biogas achieves about 50 percent conversion efficiency in 150 days.

LITERATURE REVIEW

Little background information exists to define the requirements for dry anaerobic fermentation. Buswell (Buswell and Hatfield, 1936) developed a reactor especially designed for fibrous materials in the late 1920's and Ducellier and Isman (Lesage and Abeit, 1952) used silos filled with manure and bedding as methane generators. Little information on the kinetics or the economics of these systems were found.

Two early studies achieved successful digestion of sewage solids at 20% solids and greater (Schulze, 1958, and Keefer, 1947). Recently, the feasibility of achieving efficient methane production from high solids organics has been under review by the Cornell project and others (Dynatech, 1979; Wong Chong, 1975). In a small laboratory scale study in 1976 it was shown that the rate of conversion of a mixture of straw and dairy cow manure with initial solids at 25 percent dry matter and the efficiency of conversion were surprisingly close to control decay rates in a 10 percent solids mixture (Jewell et al., 1978).

Subsequent to this initial feasibility study, Wujcik and Jewell (1979) conducted comprehensive studies of the effects of water content on the role of methane production via mesophilic anaerobic fermentation. This study attempted to define the limits that moisture and chemicals (ammonia and other salts) had on the hydrolysis reactions, the acid-forming mechanisms and finally methane production. Some data from this study will be reviewed. This study confirms the potential for starting and controlling the dry anaerobic fermentation reaction.

EXPERIMENTAL APPROACH

The Cornell University dry fermentation research began with an effort to define the role of water in methane fermentation and has become the major focus for farm- and community-scale systems. The details of the experimental designs have been published (Jewell et al., 1978; Jewell et al., 1980; Wujcik and Jewell, 1979; Jewell et al., 1981). In general, experiments have been oriented towards practical development of the concepts, with the use of natural substrates in most experiments (corn stover and wheat straw). Experiments have been conducted at bench scale (0.5 to 20 liters) and at pilot scale (4 m^3), and attempts to scale up to a 20-ton size are planned for the fall of 1981.

The definition of requirements for the dry fermentation process is proving to be difficult due to the large number of system variables. Figure 1 outlines the parameters that need to be considered in development of the process. There are 21 major parameters that affect the economic and technical

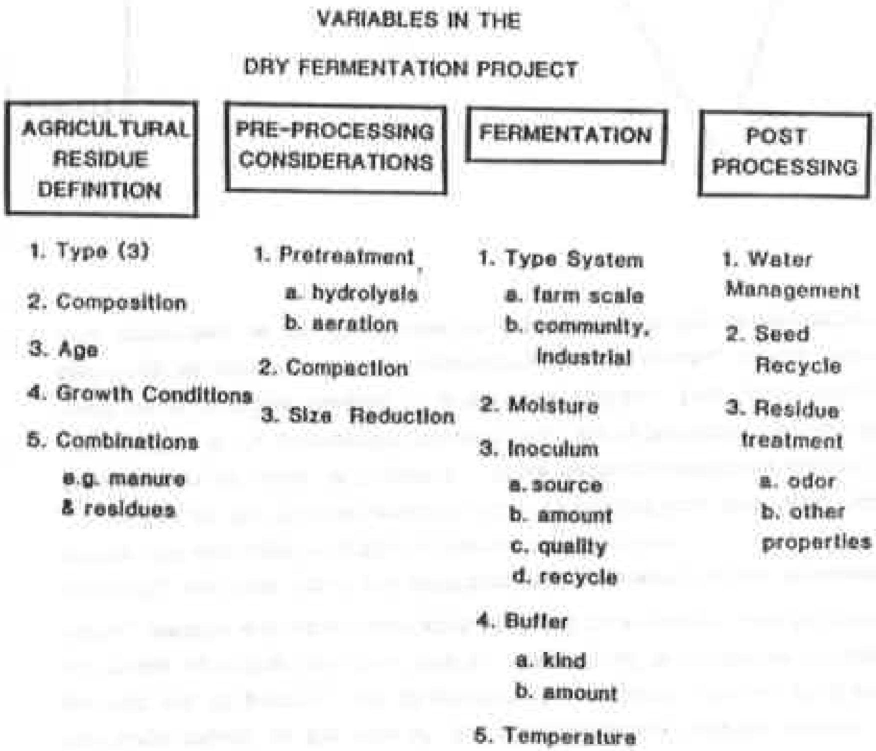

Figure 1. Major components of a dry fermentation energy system for use with crop residues.

feasibility of the system. Thus, thousands of fermentor trials will be required before the process will be thoroughly understood.

A simple computer model was developed to assist in review of the economic feasibility. A brief overview of the results is given here.

Only example data produced from the first 18 months of a large research effort are included here. More comprehensive information is available elsewhere (Jewell et al., 1981), and a second year annual report will be available in early 1982. A final feasibility analysis and preliminary optimal designs will be prepared in 1982.

RESULTS

Influence of water content

The influence of water on cow manure fermentation was summarized by Wujcik (1980), as shown in Figure 2. The important factor to note in this figure is

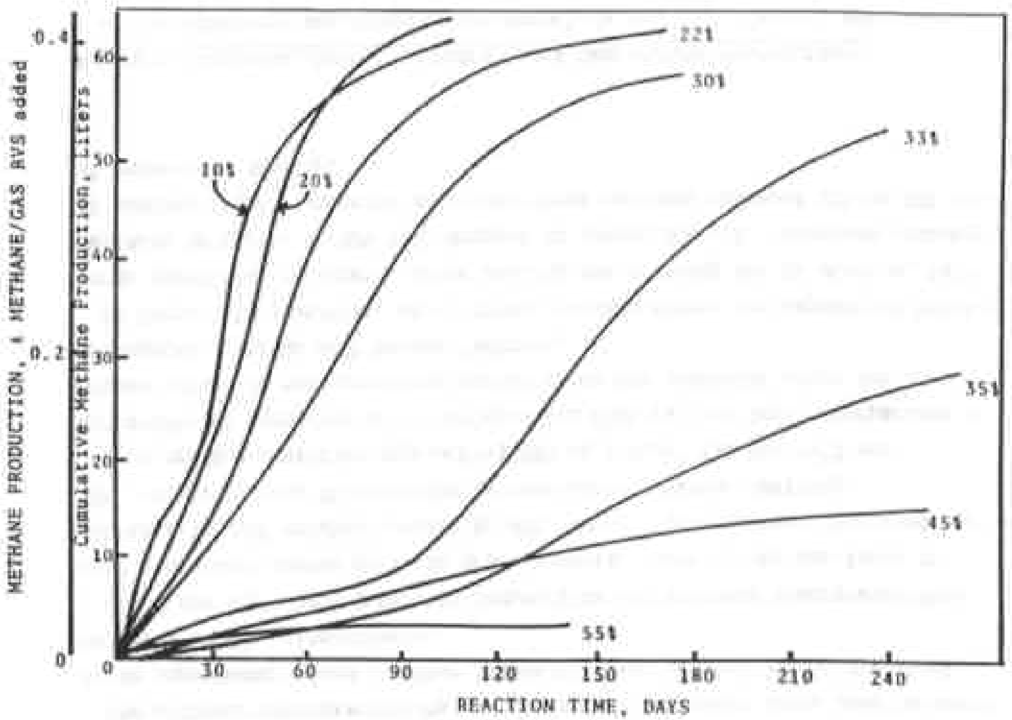

Figure 2.

Influence of moisture content on methane production rate from dairy cow manure with varying water content (Wujcik, 1979). Percent values indicate initial solids in the wet weight.

the large change in the rate of the reaction between solids content of 30 percent and 35 percent. At 30 percent the reaction rate was similar to almost all rates at higher moisture levels. Testing of the relative influence of salts, ammonia and water indicated that moisture content was the most limiting variable, and that rates and efficiencies of conversions up to about 32% solids did not significantly influence the reaction.

A review of the highest volatile acid concentrations that occurred in dry fermentation is shown in Figure 3. Since methane production becomes limited around 32%, it is interesting to note that the hydrolysis reaction becomes limiting at a solids content of around 60% solids. This would indicate that there may be possibilities of separating the two phases, solids hydrolysis and acid formation, as an alternative in optimizing the dry fermentation process.

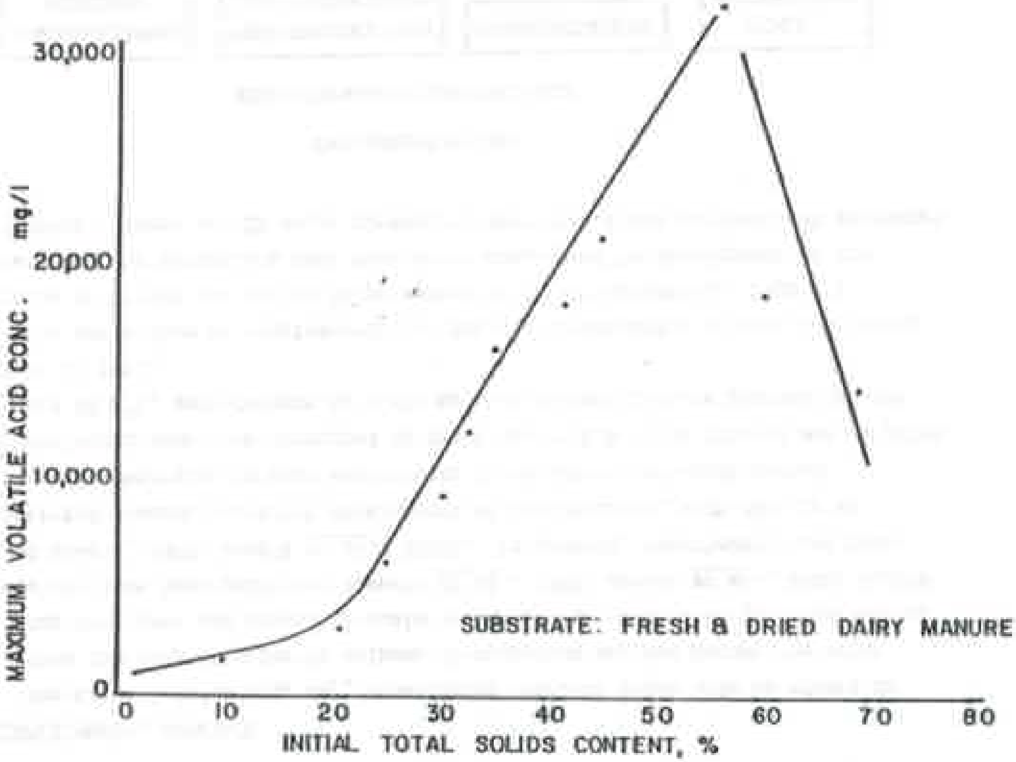

FIGURE 3. PLOT OF MAXIMUM VOLATILE ACID CONCENTRATION VS. INITIAL TOTAL SOLIDS CONTENT FOR MOISTURE STUDY BATCH REACTORS.

Agricultural residue characteristics

The ultimate biodegradability of corn stover and wheat straw used in bench scale experiments based on fiber composition was 66% and 58% of the total volatile solids, respectively.

Field age may affect substrate composition and ultimate biodegradability over a six-week period prior to grain harvest. Corn stover was found to decrease in cell soluble content by 45%, while lignin content increased nearly 40%, resulting in a 7% reduction in corn stover biodegradability.

Crop residue densities approaching 480 kg T.S./m^3 (30 lbs/ft^3) are achievable at pressures of 689 kilopascals (100 psi) or less. Compaction to higher values is not considered useful since the available water for the biological reaction will become limiting.

At loose-fill densities, wheat straw and corn stover are capable of holding large quantities of water. After soaking and draining for 15 minutes, both residues initially at 90% T.S. dropped to almost 20% T.S. Complete recovery of soaking liquids occurred only when these residues achieved 15% to 20% T.S. at loose-fill density.

Moisture, inoculum, buffer, substrate and temperature interactions

At low substrate densities (approximately 6 lbs/ft^3), initial substrate total solids contents of 30 percent or less are required to achieve good performance (90% BVS_0 in less than a year).

Successful start-up of corn stover and wheat straw dry fermentors in the range of 15% to 30% I.T.S. is more dependent on the quantity of digested dairy cow manure seed than substrate initial total solids content.

The quality and quantity of inoculum is of major concern since it will ultimately dictate several components of the system. For example, it would greatly simplify the requirements if raw manure could be utilized. Numerous experiments have shown that successful initiation of the dry fermentation reaction with only raw cow manure is difficult, if not impossible. Several units have resulted in efficient carbon conversion to biogas when starting with large quantities (30 to 40 percent by dry weight) of raw manure, but most units fail to start.

The alternative to the addition of a large inoculum rich in methanogenic bacteria would be to recycle a portion of the digested mass at completion of the reaction. Experimental trials in this area look promising.

The conversion of corn stover was more efficient than wheat straw at each temperature studied. Significant differences in the rate and extent of fermentation achieved at each temperature studied were observed. Corn stover fermented 1.75 and 3.5 times faster at 55°C than at 35°C and 25°C, respectively. Wheat straw rate differences between 55°C and 35°C reactors were not as dramatic.

Numerous experiments have been completed to identify the influence of many reactor variables on corn stover and wheat straw and more recently with old grass. An example of some of the data from the ongoing study are shown in Figures 4 to 7.

The influence of moisture, temperature, and inoculum with a mesophilic effluent on the reaction rate are illustrated in Figure 4. This seems to indicate a substantial influence of inoculum (S/F in dry weight ratio) on the efficiency over a 70-day period.

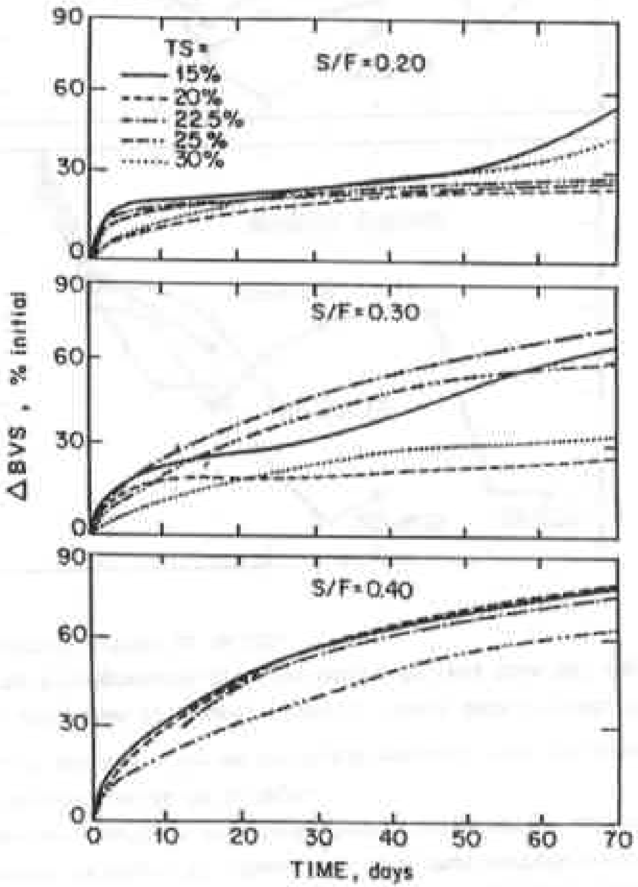

Figure 4. Percent BVS_D for corn stover at S/F = 0.20, 0.30, and 0.40 at 15%, 20%, 22.5%, 25%, and 30% initial T.S. at 35°C.

Because of the potential for increasing the reaction rates with increasing temperature, initial screening was conducted with two substrates at thermophilic temperatures (55°C) (Figure 5). The initial results indicated an extremely high reaction rate. Volumetric gas production rates were incresed to peak values greater than 7 volumes of biogas per volume of reactor per day (v/v/d). An average reaction rate of greater than 3 v/v/d over a 60-day period resulted in a 60% total volatile solids conversion efficiency. At the beginning of these studies, the goal was to obtain a dry fermentation reaction rate equivalent to the conventional designs, a value of around 1 v/v/d. These thermophilic rates raise the possibility of a highly cost-effective design alternative.

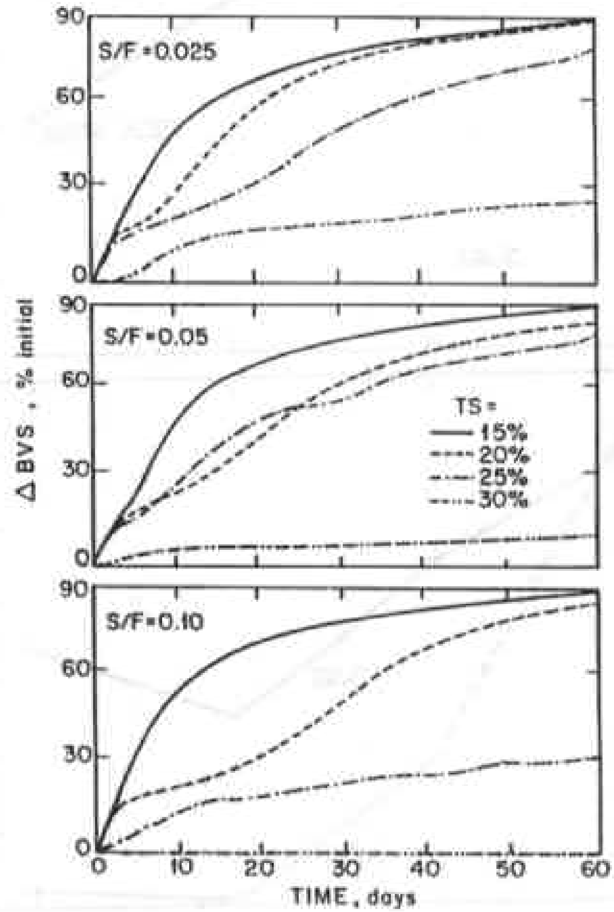

Figure 5. Percent BVS_D as a function of S/F for corn stover at 15%, 20%, 25%, and 30% initial T.S. at 55°C.

A summary of the interactions of the major variables at thermophilic conditions is shown in Figure 5. These data show that certain combinations with corn stover can result in efficient biodegradable matter conversion in a period of time as short as 30 to 50 days.

The influence of the variables on the batch reaction rate for wheat straw and corn stover are shown in Figures 6 and 7. These data indicate that 90% conversion of the biodegradable fraction occurs in less than 200 days at 35°C and 55°C with initial solids up to 28%.

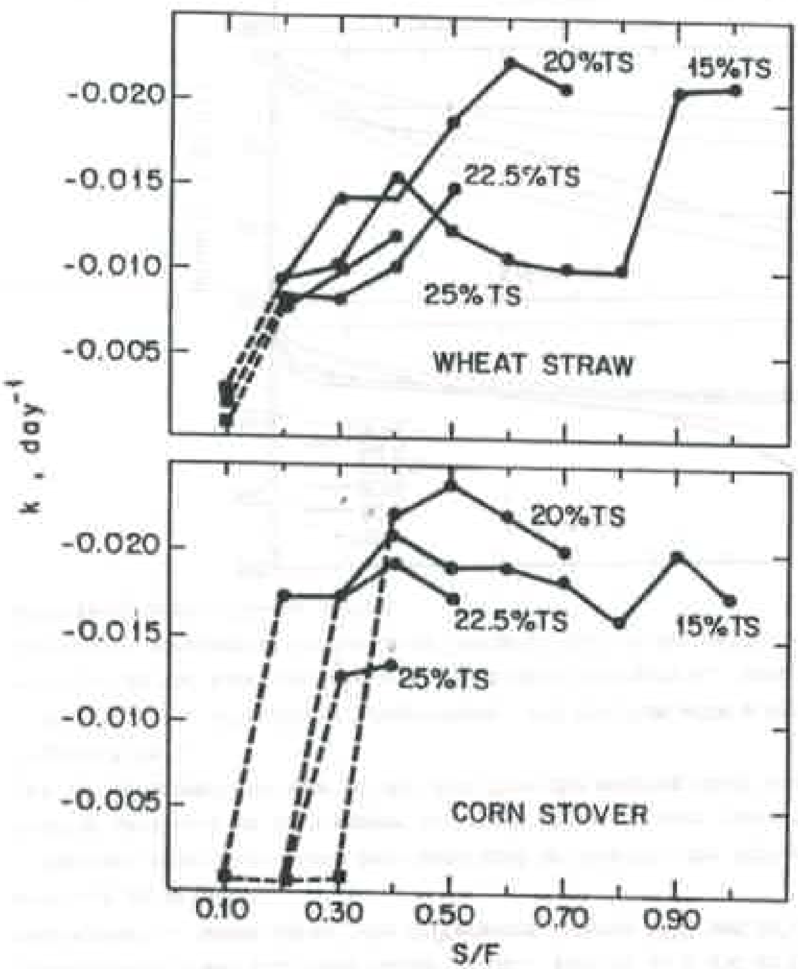

Figure 6. Effect of S/F on k for wheat straw and corn stover at 15%, 20%, 22.5%, 25% initial TS at 35°C (· = successful unit; o = unsuccessful unit).

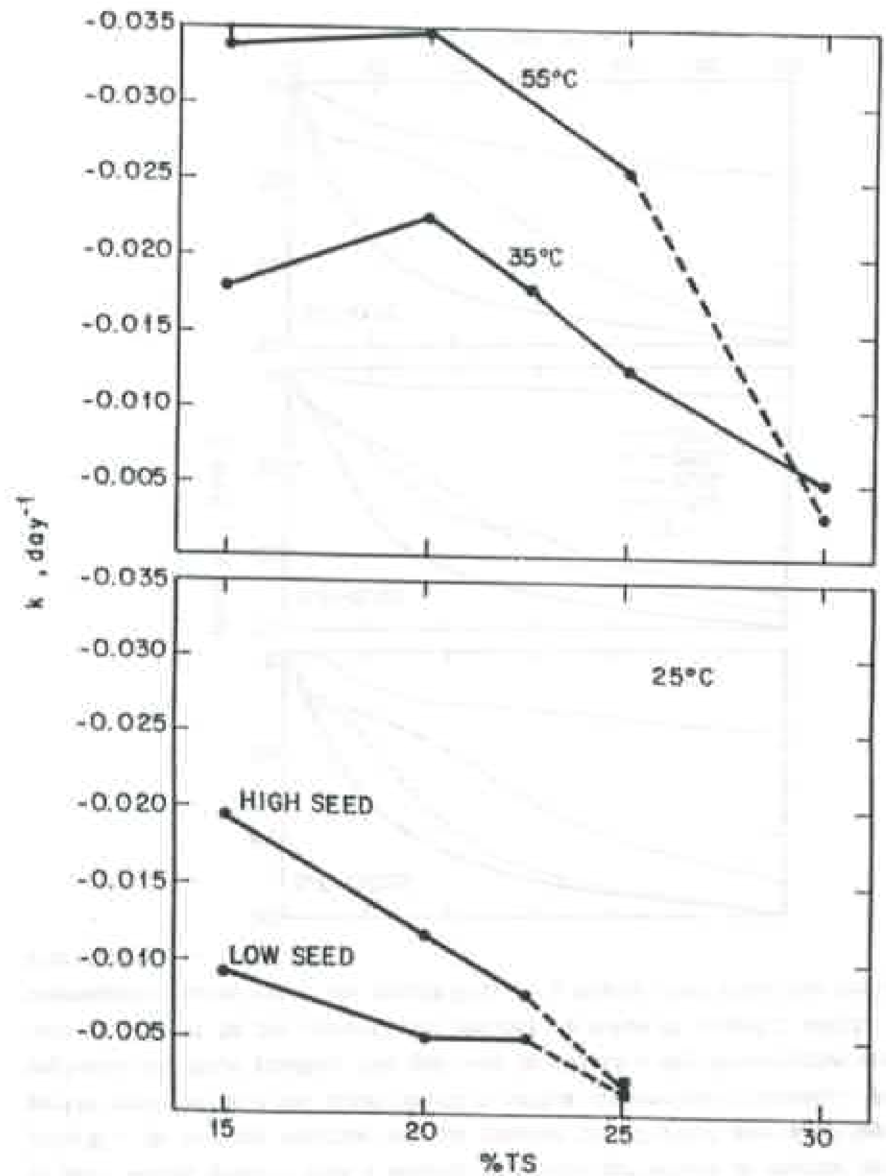

Figure 7. Effect of temperature and substrate moisture content on k for corn stover at 55°, 35°, and 25°C.

Hydrolysis pretreatment

Hydrolysis of wheat straw at 25°C, 35°C, and 55°C without pH control showed little effect of temperature on the solubilization rate or ultimate yield of soluble products. Maximum COD solubilization of 22% was attained after 11 weeks of batch hydrolysis at 25°C and 35°C. Over 90% of the available solubilized volatile acids and COD were removed by six to seven weekly stripping passes with water.

A large fraction of the soluble COD, generally 50%, was composed of organic products other than volatile fatty acids.

A two-stage digestion system started with fresh wheat straw at 75% initial total solids achieved solubilization and removal of 18% of the organic fraction after eight weeks; the two-stage system initiated with prehydrolyzed (for 11 weeks) wheat straw at 45% initial total solids achieved removal of 22% after eight weeks of stripping.

The soluble COD in leachate from 12 weeks of batch hydrolysis at 25°C and 35°C was found to be 73% biodegradable after 25 days digestion in serum bottles at 35°C. Soluble COD in leachate from acid-stripped reactors declined rapidly in biodegradability over the first six weeks of stripping.

Scale-up potential

Results comparable to that achieved in bench scale reactors were obtained by 5 m^3 pilot scale reactors four orders of magnitude greater in size at thermophilic conditions.

Based on gas production data, the corn stover pilot scale reactor at 55°C, 25% I.T.S., 0.025 S/F, and 0.08 B/F achieved 33% T.V.S.$_{D}$ and 56% B.V.S.$_{D}$ in 60 days. Volumetric biogas yields from this unit were greater than 1 v/v/d and 0.5 v/v/d for 12 and 32 days, respectively, at a substrate density of 169 kg/m^3 (10.5 lbs/ft^3).

The wheat straw pilot scale reactor operating under identical conditions to that of the corn stover pilot scale reactor exhibited relatively poor performance, averaging 160 liters biogas per day (0.05 v/v/d) for over 40 days at a methane content ranging from 35% to 48%. Analysis of earlier 55°C bench scale data indicated that insufficient inoculum was used to start up this reactor. Smaller scale ongoing studies show that an inoculum of up to 10 percent of the dry weight may be required. Further analysis showed that when the methane production system fails to be initiated, the biodegradable organic carbon is rapidly destroyed at the thermophilic temperatures. Apparently the complex "browning reactions" caused by the high temperatures were responsible

Preparation of dairy cow manure seed used in this study indicated that success of dry fermentor start-up may be dependent on the condition and quality (number of viable methanogens) of the inoculum.

System feasibility and economics

The complex interactions of mixtures of crop residues and animal manures with the major process variables indicate that the farm-scale system definition will result in a cost-effective system with further definition. Because of the large number of variables, the problem of evaluating the feasibility of centralized facilities where large quantities of crop residues would be transported is highly complex. To evaluate the economic feasibility, a dry fermentor model was developed that incorporated all major components of the system, and these are summarized in Table 2. Preliminary results from the program are shown in Tables 3 and 4. The cost of the substrate is not included, but the final costs can be contrasted against the income that may be derived. Also, the values of the fermented residues are conservative estimates. An optimistic or best case, worst case, and one that combines existing equipment and values into what one might expect to achieve with a practical system are shown. The more practical system has a resulting net gain or profit of $14 per ton. Collection of crop residues from a radius of 10 miles would provide all of the natural gas requirements for a population of 11,300 people. No crop residue value is assumed in this case for the 30,000 tons per year that would be produced. Under the worst case, the energy value would have to be $18 per million Btu for the facility to operate without a loss.

TABLE 2

COMPONENTS OF A COMMUNITY-SCALE DRY FERMENTATION SYSTEM CONSIDERED IN AN ECONOMIC FEASIBILITY MODEL

Harvesting Method	Processing
Transportation	a. Reactor
a. Labor	b. Manure storage
b. Fuel	c. Chemical and water addition
c. Method	
Prehandling	Residue Recovery
a. Chopping	
b. Moving	By-product Handling
c. Compression	By-product Marketing

TABLE 3

SUMMARY OF INPUT VARIABLES FOR ECONOMIC FEASIBILITY ANALYSIS OF THE CENTRALIZED CROP RESIDUE DRY FERMENTATION SYSTEMS. (COLLECTION DISTANCE 10-MILE RADIUS)

	Example		
	Worst Case	Potentially Feasible	Best Case
Substrate	Corn Stover	Corn Stover	Corn Stover
Substrate Cost	-0-	-0-	-0-
Substrate Transportation			
Stack wagons	must be purchased ($2000)	must be purchased ($1000)	farmer-provided
Fuel cost, $/gal	2	1.27	1
Labor, $/hr	5	6	0
Interest rate	12	16	5
Land contributing substrate, %	30	15	70
Reactor Conditions			
Solids content, % dry weight	20	35	35
Bulk density, lb-dry/ft^3	18	18	25
Seed/feed (dry wt)	0.2	0.05	0.05
Buffer/feed (dry wt)	0.2	0.025	0.02
Buffer cost, $/ton	50	20	20
Efficiency, % converted	45	50	60
Loading rate, times/year	1	3	3
Product Values			
Methane, $/10^6 Btu	4	3.5	6
CO_2, $/ton	0	60	60
Residue value	15	0	30
Residue dried to 50% solids	yes	no	no

TABLE 4

EXAMPLE RESULTS FOR VARIOUS INPUT ASSUMPTIONS (AS SHOWN IN TABLE 3.) FOR CENTRAL FACILITY CROP RESIDUE DRY FERMENTATION FACILITIES COLLECTING CORN STOVER RESIDUE FROM A 10-MILE RADIUS.

	Example		
	Worst Case	Potentially Feasible	Best Case
Harvesting and transportation costs, $/ton	41	3.0	4.10
Crop residue harvested, tons dry	60,300	60,000	422,000
Reactor volume 10^{3}ft^3	5,630	2,320	5,020
Total Cost, Million $	7	5.2	42
Energy produced, 10^3 million Btu/yr	214	426	6,170
Equivalent population served, numbers of people	5,200	11,300	14,900
Annual revenue, million $/yr	(-3.3)	0.84	33
Net income, $/ton	(-54)	14	80
Breakeven cost of methane, $/million Btu	18	--	--

DISCUSSION AND CONCLUSIONS

The conversion of relatively dry organics directly to biogas increases the potential of using large quantities of organics that are presently available. Examples include mixtures of crop residues and animal manures on the farm, crop residues, and urban solid wastes. Besides the use of the dry fermentation process on farms and in centralized facilities, the possibility of using this concept as a residential energy generating system exists.

Crop residues can be used to generate biogas without generating major water needs or problems. Requirements for an efficient reaction include initial solids content of less than 30% solids, an active methanogenic slurry added at between 5 and 40 percent of the dry weight (depending on the substrate), and a reaction period of between 60 days and 300 days, depending on the reactor temperatures.

This study began with a requirement to minimize the process requirements while increasing the reactor rates to a level that would be equal to or greater than conventional process rates. Presently, we have achieved reaction rates that exceed any other process. Process constraints such as buffer and inoculum requirements also appear to have less costly alternatives. With these reduced system requirements it is likely that crop residues can have a major role in future biogas production schemes. Further analyses are required to clarify the controlling parameters and economic feasibility.

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Key research activities in defining the dry fermentation concept were initially conducted by J. A. Chandler, W. J. Wujcik, and A. P. Leuschner. Dr. E. E. Koslow developed the computer systems model. Other members who assisted the research team are R. J. Cummings, P. J. Van Soest, J. B. Robertson, D. M. Harbert, and J. A. Spada. Activities on this research project are scheduled to continue through 1982.

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