Methods to Recover Nutrients and Energy from Swine Manure

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ABSTRACT

Disposal of manure is a major problem, yet manure could be a valuable resource. It is a source of digestible organic material, plant nutrients, and protein. This report describes methods for the recovery of energy and protein from swine manure. Energy and material balances are presented for several management systems with emphasis on one designed to maximize recovery of biogas and a second one designed to maximize recovery of protein. Analyses compare the energy needed to produce the feed for 100 pigs and raise them with the energy which can be derived from the manure discharged by these pigs. The protein needs of the 100 pigs are compared with the protein which could be recovered from the manure by means of fermentation processes or by growing algae. Since the C/N ratio of the manure is low, yield of biogas and protein can be increased by adding properly treated straw. On-farm energy needs are about 85 Mkcal/yr (million kilocalories per year). When biogas recovery is emphasized, the manure yields 38 Mkcal/yr without straw added and 121 Mkcal/yr with straw added. The protein needs are about 13,000 kg/yr. A farmer could recover 27 Mkcal/yr of biogas and 4,000 kg/yr of protein or 59 Mkcal/yr of biogas and 6,500 kg/yr of protein with straw added.

Interpretations of data in the report should be made with care. The proposed systems have not been operated under "real world" conditions. The report presents potential processes that have considerable promise for successful development through further research. It does not give an account of existing technology.

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METHODS TO RECOVER NUTRIENTS AND ENERGY FROM SWINE MANURE

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PART I: BIOGAS

Introduction

Manure stinks! Special precautions must be taken to store it. Discharge to surface waters causes eutrophication. Storage and treatment are a nuisance to the farmer because of the bad smell and the cost. Yet manure is hailed also as a valuable resource. It is a source of digestible organic material, plant nutrients, and protein. Many methods for the use of manure have been proposed. But few are used by farmers. We wanted to know why efforts to recover useful products from this seemingly valuable resource have not been more successful. We did so by obtaining energy and material balances of several methods for the management of swine manure. The methods, sometimes referred to as bioconversion, are based on the use of microorganisms to convert the manure into feed and biogas.

The cells of microorganisms such as algae, yeasts, microfungi, or bacteria contain high quality protein, often referred to as "single cell protein" or SCP. This nomenclature avoids unpleasant connotations relative to food which might be associated with such terms as "bacterial" or "microbial". The advantages of these organisms, in addition to their high protein content, are the possibility of growing them during the entire year and the potential for technological management.

Solids in the manure consist of cellulose fibers, bacterial cells, spilled feed, hairs, and other debris. These materials can be broken down into methane (CH_4) and carbon dioxide (CO_2) by anaerobic microorganisms. Prominent among these are the methane bacteria.

The dissolved organic matter together with dissolved nitrogen (N) can be used by yeast and microfungi as a source of food to produce cells rich in protein. The dissolved minerals can be used by algae, which use low energy substrates together with the input of light energy, to produce cells rich in protein.

Successful implementation of bioconversion methods would have several benefits to society. Among these are improved efficiency of energy use and food production, elimination of pollution problems, recycling of raw materials, and conservation of non-renewable resources. The methods discussed here are combinations of bioconversion processes.

Interpretation of this Report

This report describes methods to recover energy and protein from swine manure. Energy and material balances are presented for several systems of management for the manure with emphasis on one designed to maximize the recovery of biogas and a second one designed to maximize the recovery of protein. The analyses compare the energy needed to produce the feed for 100 pigs and raise them with the energy which can be derived from the manure discharged by these pigs and the protein which can be grown using dissolved organic matter in the manure as a substrate.

The protein needs of the 100 pigs are compared with the protein which could be recovered from the manure by means of fermentation processes or by growing algae. Although the report is based on results of experiments carried out at Oregon State University and at other research institutions, it is, to a large extent, of a theoretical nature. Several of the recovery processes described have not been tested under experimental conditions or under "real world" operating conditions. Furthermore, certain losses which are known to occur have not been taken into consideration in the preparation of energy and nutrient balances. For example, the report traces the pathway of nitrogen from the field, to the manure, and from it to recovered protein. It shows how much nitrogen may be expected to be discharged in the manure and then proceeds to develop methods of recovery of this nitrogen in the form of protein. Losses of nitrogen occur in the form of volatilization of ammonia gas. The rate of these losses depends on several operating conditions which are not well known. In our analysis, we have assumed a certain percentage of loss. However, no documentation for this assumption is presented. Finally we note that certain assumptions used may be subject to change in further detailed analyses. For example, our analysis is based on protein content of

12 percent in the feed. This protein content is low for growing pigs although adequate for a maintenance diet. Feed additives were not taken into account. As a result the level of phosphorus in the feed is also low. However, refinement of these estimates is not expected to change the conclusions very much.

The intent was to show the potential for protein recovery as an incentive to increase efforts towards the development of and design of systems to achieve these production levels. For example, the report suggests that the manure should be collected in a pit below the floor on which the pigs are kept and then a small volume of water should be used to pump the manure to fermenters. Systems to do this have not been developed. If the water and manure are allowed to remain in the pit for long periods of time, to achieve a substantial accumulation of it, significant nitrogen losses and biological energy losses may occur. This the reader must keep in mind while reading the report.

The production of yeast and microfungi, using the manure as a substrate, is discussed. Such systems have not been operated with swine manure. The reader should be aware of the fact that the report presents potential processes that could be developed by further research. The reader should not assume that the information which has been presented is a report about existing technology.

While evaluating the discussion of production of biogas, it should be kept in mind that a portion of the gas is needed to maintain the digester at a temperature of $35^{\circ}C$ to achieve optimum rate of production. Thus, not all the biogas produced is available for energy use in other farming systems. In cold climates, the energy demand for heating could be substantial.

One of the most uncertain aspects of the management techniques described in the report is the utilization of straw as an additional cellulose containing waste products. Straw cannot be used for microbiological digestion without pretreatment. Although rapid progress is being made in developing pretreatment techniques, uncertainties in this area remain. These uncertainties are discussed in detail in the report.

Energy and Material Balances

Energy and material balances were developed based on the feed energy needs and waste discharge of 100 pigs. The information presented in Figure 1 is from our own measurements and experiences (Boersma et al., 1978) as well as from literature reports.

It is assumed that the pigs initially weigh 50 kg each and are fed to reach a final weight of 100 kg. The gain in weight is 0.80 kg/pig/day and the ratio of gain/feed is 0.263. The amount of feed consumed is therefore 3.04 kg/pig/day. Each pig discharges three liters of fresh manure per day containing 14% by weight (w/w) of solids or 0.42 kg. The duration of the feeding period is 50/0.80 = 62.5 days.

Feed

For this report, we assumed a simplified ration of corn and soybean meal. In most rations, other sources of protein and energy are substituted including barley, wheat, cottonseed meal, fish meal, alfalfa, or whey. Salts, vitamins, and antibiotics also are added.

The amount of feed for 100 pigs is 304 kg/day. It contains 12% or 36.5 kg crude protein of which 75% or 27.4 kg is contributed by the corn and 25% or 9.1 kg by the soybean meal. The feed contains 283.7 kg of corn with a protein content of 9.65% and 20.3 kg of soybean meal with a protein content of 45%. The nitrogen (N) content of the daily ration is 5.84 kg.[1/]

We assume 0.35% or 0.99 kg and 0.70% or 0.14 kg of phosphorus (P) in the corn and soybean meal, respectively, for a total of 1.13 kg in the daily ration. The corresponding values for potassium (K) are 0.40% or 1.13 kg in the corn and 1.80% or 0.37 kg in the soybean meal for a total of 1.50 kg. The 100 pigs gain a total of 80 kg/day. The added weight contains 2.56% N, 0.18% P, and 0.25% K on a w/w basis. The pigs therefore retain 2.05 kg N, 0.15 kg P, and 0.20 kg K per day or 35.1% of the N, 13.3% of the P, and 13.3% of the K in the feed. By difference, 3.79 kg N, 0.98 kg P, and 1.30 kg K per day are discharged with the feces. In addition, we assume that 5% of the feed is spilled and added to the manure.

[1/] These discussions are based on the assumption that the nitrogen content of protein is 16%.

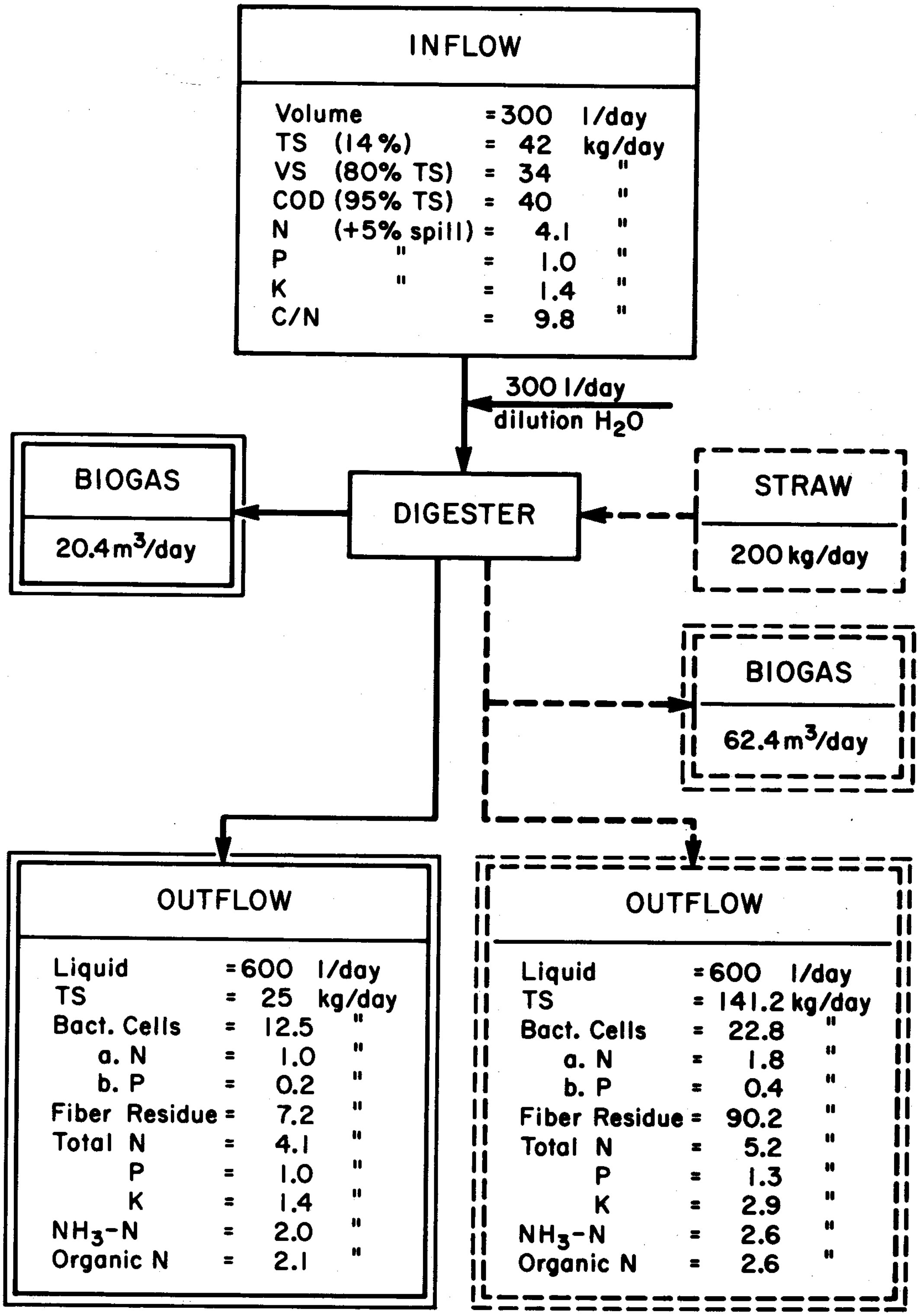

Figure 1. Material balances for the manure discharged by 100 pigs, being fed to gain weight from 50 to 100 kilograms (kg) at the rate of 0.8 kg/day. The manure is routed to a digester for production of biogas. Similar balances are shown for a system of management where straw is added to the digester for increased gas yields.

Land Area

The land area needed for growing the feed can be estimated by assuming that consecutive groups of 100 pigs are fed throughout the year. This implies that 350/62.5 = 5.6 groups of pigs are raised from 50 to 100 kg, leaving 15 days for change between groups. The requirement for soybean meal is 20.3 x 350 = 7,105 kg/yr and for corn 283.7 x 350 = 99,295 kg/yr. Assuming yields of 8,000 kg/ha/yr for corn grain and 2,490 kg/ha/yr for soybean meal (83% of 3,000 kg/ha/yr), the land areas required for growing the feed are 12.41 ha for corn and 2.85 ha for soybeans, or a total of 15.26 ha. The number of pigs fed during one year is 560 which corresponds to 36.7 pigs/ha.

Left behind in the fields are the straw and stover which amount to 8,000 kg/ha/yr for the corn or a total of 99,280 kg/yr and 3,500 kg/ha/yr for the soybeans or a total of 9,975 kg/yr. The total amount of straw is 109,255 kg/yr. We assume that 75% of the straw or 81,941 kg/yr can be removed without detriment to the land. The root systems contain 5,000 and 2,000 kg/ha/yr for the corn and soybeans, respectively, for a total of 67,750 kg/yr.

Energy Requirements

The amount of solar energy captured by the plants can be calculated by assuming a combustible energy content of 4,500 kcal/kg (Table 1). The assumption indicates that the corn captured 94.5 x 10^6 kcal/ha/yr (grain: 36.0 x 10^6; stubble: 36.0 x 10^6; roots: 22.5 x 10^6) and the soybeans captured 38.2 x 10^6 kcal/ha/yr (beans: 13.5 x 10^6; stubble: 15.8 x 10^6; roots: 9.0 x 10^6). The total amount of solar energy captured is, therefore, 1,282 x 10^6 kcal/yr (corn: 1,173 x 10^6; soybeans: 110 x 10^6). Farming operations, including labor, machinery, fuel, fertilizers, seeds for planting, insecticides, herbicides, irrigation, transportation, and drying require an estimated 7.1 x 10^6 kcal/ha for a total of 108.4 x 10^6 kcal/yr (Pimentel et al., 1975). About 50% of this is in the form of direct energy expenditure on the farm in the form of fuel and electricity, about 30% is for the mining and manufacturing of fertilizers, mainly nitrogen, and the remaining 20% is for labor, pesticides, herbicides, and production and maintenance of machinery. The total amount

Table 1. Energy values of several products used and produced on a farm where pigs are raised from 50 kg to 100 kg per pig. There are 100 pigs at all times.

		10^6 kcal/yr
SOLAR ENERGY		
Corn (12.41 ha)		
grain (99,295 kg/yr)		447
straw (99,280 kg/yr)		447
roots (62,050 kg/yr)		279
	Total	1173
Soybeans (2.85 ha)		
beans (meal) (7,096 kg/yr)		32
beans (oil) (1,454 kg/yr)		7
straw (9,975 kg/yr)		45
roots (5,700 kg/yr)		26
	Total	110
FARMING OPERATIONS		
cultural energy		108
livestock housing and care		24
feed processing		8
PRODUCTS		
pork (19,600 kg/yr)		59
biogas		
no straw (7,140 m^3/yr)		38
with straw (22,776 m^3/yr)		121
nitrogen (1,435 kg/yr)		25
phosphorus (350 kg/yr)		1
potassium (490 kg/yr)		1

and distribution varies with the farming system. These estimates are considered to be reasonable approximations. They are important because the rate at which energy can be produced in the form of biogas will be compared with the rate of energy expenditure on the farm in the form of fuel and electricity.

Additional energy is required for the husbandry of the pigs. These requirements are estimated to be 24 x 10^6 and 8 x 10^6 kcal/yr for the livestock operations and feed processing, respectively (Table 1).

Yield of Pork

Our analysis is concerned with feeding groups of pigs from an initial weight of 50 kg/pig to a final weight of 100 kg/pig. About 70% of the final weight is available for consumption. This percentage varies according to local customs. The yield of useful product is, therefore, 19,600 kg/yr. This represents 58.8 x 10^6 kcal of digestible energy, assuming an average of 3,000 kcal/kg (ham: 2,000; chop: 2,700; fat roast: 3,700; lean roast: 2,600; links: 4,800). The efficiency with which the total amount of solar energy captured by the plants is converted to food energy, therefore, is 4.6%. The digestible energy in the pork represents 12.3% of the combustible energy in the feed grain, 15.8% of the digestible energy in the feed, and 9.4% of the total energy input (Table 2).

Manure

The manure consists of the excrements, spilled feed, and bedding material. Here, only excrements and 5% spilled feed are considered. The volume of discharge is 300 l/day with 14% (w/w) solids or 42 kg/day. Additional information is in Figure 1. Use of bedding material could change characteristics substantially.

The protein digestibility of the feed is 75% so the pigs excrete 0.25 x 36.5/6.25 = 1.5 kg N/day in the feces. Of the 27.4 kg of protein absorbed by the pigs, 53% is discharged in the urine, corresponding to a N loss of 27.4 x 0.53/6.25 = 2.3 kg/day. This N is mostly in the form of urea which is readily converted to ammonia by bacterial activity.

Table 2. Energy inputs and outputs for a farming operation in which 100 pigs are raised from 50 kg to 100 kg. The numbers shown pertain to a period of one year.

Category		No straw		With straw	
		Energy content	% of total input	Energy content	% of total input
		10^6 kcal	%	10^6 kcal	%
ENERGY INPUT					
corn grain		447	72.2	447	47.1
soybeans		32	5.2	32	3.4
straw		--	--	330	34.8
farming:					
fuel & electr.	54.2				
fertilizers	32.5				
labor & mach.	21.7				
livestock maint.	24.0				
feed processing	8.0				
	140.4	140	22.6	140	14.8
Total		619	100.0	949	100.0
ENERGY OUTPUT, USEFUL PRODUCTS					
pork		59	9.4	59	6.2
biogas		38	6.1	121	12.7
N		25	4.0	25	2.6
P		1	0.2	1	0.1
K		1	0.2	1	0.1
		124	19.8	207	21.7
ENERGY SINKS					
heat loss from pigs		254	41.0	254	26.8
CO_2 and other gases		120	19.4	340	35.8
other (e.g. fiber residue)		121	19.5	148	15.6
		495	79.9	742	78.2

Thus, the pigs may be expected to excrete a total of 3.8 kg N/day. The spilled feed contains 0.3 kg N/day so the manure contains a total of 4.1 kg N/day. The N is mostly in the ammonium form. The remainder is in dissolved organic matter and in suspended organic solids. The manure contains 1.0 kg P/day and 1.4 kg K/day. The C/N ratio is 9.8.

Methane and Fertilizer

Process Description

The simplest method to recover useful products is to route all the fresh manure into an anaerobic digester to produce biogas and to solubilize plant nutrients.

The 300 liter (l) of fresh manure produced each day by the 100 pigs must be diluted with about 300 l of water to make the suspension easier to pump and to reduce the concentration of total solids in the digester to about 7% (w/w). A range of 7 to 9% is recommended for optimum operation of the digester. It may be necessary to dilute the manure more to avoid ammonia toxicity which occurs at concentrations of ammonia N above 1,200 mg/l and to avoid production of volatile fatty acids in excess of 5.9 kg/m^3/day.

The volume of dilution water is not sufficient to operate a gutter flushing system. The pigs, therefore, must be kept on slatted floors with the manure collecting in a pit below. The manure is mixed with water in the pit and then pumped into the anaerobic digester.

Optimum digestion is obtained with retention times of 10 to 17 days. The digester must be large enough to store the volume of manure produced during this period. The size is determined by the preferred volume of dilution water and retention time. For example, a retention time of 15 days and an inflow of 800 l/day (300 l manure with 500 l dilution water) requires a volume of 12 m^3. Continuous operation is accomplished by adding diluted manure each day and allowing an equal volume of digested waste to flow into a storage tank or holding pond.

Product Yields

The manure discharged by the 100 pigs each day contains 34 kg of volatile solids (Meek et al., 1975). The amount depends on composition of feed, bedding material, and age of pigs. Half of the VS are destroyed by the anaerobic digestion process to yield CH_4 and CO_2. The efficiency of conversion depends on temperature, loading rate, and pH. The digestion may be expected to yield from 1 to 1.4 m^3 of biogas per kg of VS removed. Volumes of gas are reported at the standard temperature of 20 C and pressure of 760 mm Hg. The biogas contains usually about 60 percent CH_4 and 40 percent CO_2. The combustible energy of the mixture is about 5,330 kcal/m^3.

The yield of biogas is 20.4 m^3/day, assuming 1.2 m^3 of biogas per kg VS removed per day. The actual yield depends on loading rate, pH, temperature, and retention time. Some variables may change substantially during the course of one year unless operating conditions are carefully controlled. The operator must have the flexibility in his management system to adjust to these changes.

The biogas recovers about 6.1% of the total amount of solar energy and cultural energy represented by the corn and soybean meal (Table 2). However, the recovery is equivalent to 70% of the energy used in farming operations.

The liquid outflow from the digester contains plant nutrients and is a good soil conditioner. All the nutrients originally present in the manure are present in the digester outflow. The availability of the N to plants has been increased because of the decrease in carbon molecules which escaped as CH_4 and CO_2.

The daily outflow contains 25 kg of dry matter which consists of 12.5 kg of bacterial cells with a crude protein content of 50 percent, 7.2 kg of fiber residue, and 4.1 kg of N including 1.0 kg of organic N in the bacterial cells (Figure 1). The fiber residues were not solubilized by the bacteria in the digester but can be utilized by fungi in the soil. On an annual basis, the total outflow from the digester contains 1,435 kg N, 350 kg P, and 490 kg K. When spread on land, each ha of the 15.26 ha of land needed to raise the corn and soybean meal for the swine ration would receive 94 kg N, 23.0 kg P, and 32.0 kg K per year. The energy value of the recovered fertilizer represents 4.4% of the total energy input (Table 2).

The use of processed sludge as a feed supplement for ruminants merits consideration. The yield of crude protein is 2,888 kg/yr. One possibility, not pursued here, would be to use the biogas for drying the sludge to make the protein useful.

Use of Biogas

Although it is possible to use the biogas as it comes from the digester, its value would be increased by removing the carbon dioxide. Removing the CO_2 from the biogas increases the energy content from 5,330 to 8,800 kcal/m^3. The techniques most frequently used in chemical plants or gas fields for separation of CO_2 from other gases are absorption in monoethanolamine or in hot potassium carbonate (Benfield process) at pressures of 14 to 34 atm. These processes are economically feasible only at flow rates in excess of 200,000 m^3/day. Adsorption of the CO_2 on molecular sieves made of natural zeolite is being evaluated as a more economical separation process at low flow rates. Methane gas can be dried by contact with activated alumina, silica gel, or triethylene glycol.

Removal of CO_2 and water from the biogas is necessary when the gas is injected into pipelines and used as a substitute for natural gas. When biogas is used on-site and on a small scale, it may be more economical to modify equipment to burn the biogas as it comes from the digester.

The heating value of the 20.4 m^3 of biogas is 108,732 kcal/day. A well insulated home with three bedrooms and a heated space of 283 m^3 requires an average of 62,000 kcal/day in Portland, Oregon, during January which has 791 degree days. The same house requires an average of 122,000 kcal/day in Minneapolis, Minnesota, where January has 1,562 degree days. If the biogas were used to generate electricity, it could produce 22 kWh/day. The average use per household is about 23 kWh/day for the U.S. and about 43 kWh/day for Oregon.

On farms, the biogas from the digester can be used for cooking, heating of water and buildings, refrigeration, or generation of electricity. Use for farm machinery does not seem to be practical. For example, a 100 hp tractor operating for one hr requires 45 m^3 of biogas. The annual yield of 7,140 m^3 would allow the use of the tractor for 158.7 hrs. This yield is promising in relation to the requirements for cultivation of the 12.41 ha of corn and 2.85 ha of soybeans needed to provide the feed for the 100 pigs.

However, a cylindrical fuel tank, 16 m long, with a diameter of 6 m is required to store 450 m^3 of the biogas which would be sufficient to run a 100 hp tractor for 10 hrs. Compressing the gas is therefore necessary. A standard sized fuel tank for a 100 hp tractor has a volume of 0.227 m^3. Storage of the amount of biogas required to fuel the 100 hp tractor for one hr, namely 45 m^3, in this volume at standard conditions would require a pressure of 205 atm. If the pressure is reduced to a more manageable 20 atm, the tractor would run for only 6 min.

The digestion process requires energy to heat and mix the contents of the digester, pump influent and effluent, and perhaps compress the gas for storage. The largest amount is needed for heating the digester and its contents. This heating requirement is determined by the outside temperature and the tank insulation. Heating to 37 C and mixing are necessary to provide optimum conditions for the growth of the bacteria in the digester. Mixing is required for only a few minutes each day.

The performance of an anaerobic digester supplied with manure from 100 dairy cows was evaluated on a commercial scale by the A. O. Smith Co., Milwaukee, Wisconsin. An experimental digester with a volume of 120 m^3 was operated for 18 months. The field installation consisted of a heated and mixed digester, a collection pit to receive fresh manure, a storage pit for the digester effluent until it could be spread on land, and a service building to house equipment and instruments. The digester was made from a grain silo with walls of glass coated steel, insulated on the outside with 5.1 cm of polyurethane. The structure was above ground. The digester was heated at 35 C and mixed intermittently for a total of about six hrs per day.

About 74% of the biogas was needed for heating the digester to 35 C during the coldest month when air temperatures averaged -9 C and 26%

during the warmest month when air temperatures averaged 24 C. The cost of producing the methane gas in excess of the heating requirements of the digester was estimated at \$11.90 to \$13.90 per 10^6 kcal. This cost compared to \$8.73 per 10^6 kcal of natural gas for home heating in the Milwaukee, Wisconsin, area. The price of natural gas varies considerably throughout the U.S. For example, the cost of natural gas for home heating in the Willamette Valley, Oregon, is \$13.90 per 10^6 kcal. The cost of producing methane gas from animal manure is more favorable in geographic areas with mild temperatures or where heat from other sources is available to maintain digester temperatures.

Increasing the Yield of Biogas

The yield of biogas with a maximum energy content is highest at a C/N ratio of about 30. The yield of methane increases as the C/N ratio approaches 30, while the total yield of biogas remains fairly constant. The C/N ratio of the swine manure used here was 9.8 (Figure 1). The yield of gas can be increased by adding materials which contain a large amount of cellulose. Usually, waste products such as straw or other crop residues are readily available for this purpose.

We calculated the amount of straw which should be added to the digester to increase the C/N ratio from 9.8 to 30. To obtain a C/N ratio of 30, 4.1 x 30 = 123 kg COD/day should be added to the digester. Since 40.2 kg COD/day is in the manure, an additional 82.8 kg COD/day must be provided by another carbon source. The estimated yield of biogas is then 123/40.2 = 3.06 times greater than without the COD added, or 62.4 m^3/day.

The straw or other material must supply sufficient carbon to yield 62.4 - 20.4 = 42.0 m^3 biogas/day. Assume a mixture of 60% CH_4 and 40% CO_2 in the biogas. Assume further that straw is used which contains 64% (w/w) of cellulose and hemicellulose with a digestibility of 45% and that the yield is 0.44 m^3 CH_4 per kg of cellulose and hemicellulose (Han, Lee and Anderson, 1974). The yield of CH_4 per kg of straw is then 1 x 0.64 x 0.45 x 0.44 = 0.127 m^3 CH_4. The total yield increase is 42.0 x 0.60 = 25.2 m^3 CH_4. The total amount of straw to be added is 25.2/0.127

= 200 kg/day or 200 x 365 = 73,000 kg/year. This amount is 67% of the straw left in the fields (Table 1) and can be harvested without detriment to the land.

By adding the straw the energy yield of the digester becomes 121 x 10^6 kcal/year or 12.7% of the total amount of solar energy and cultural energy represented by the corn, soybean meal and straw (Table 2). The biogas energy is equivalent to 223% of the energy used in farming operations.

Pre-treatment

Pure cellulose is readily digested under anaerobic conditions. However, in its natural state it is chemically bound to hemicellulose and lignin in a complex structure which is largely inaccessible to the extracellular enzymes of the bacteria in the digester. Pretreatment of the waste, therefore, is necessary. The use of either strong acids or alkali, chemical pulping, steeping in hot water or steam, irradiation with high-energy electrons, enzymatic hydrolysis by wood-rot fungi, and mechanical grinding into fine particles have been investigated. Grinding in a ball mill is probably the most practical approach for small operations. It remains to be determined whether the increase in biogas production can justify the energy consumption of the grinding process.

New Designs for Digesters

The rate at which properly pretreated wastes can be added to the digester is limited by the kinetics of methane formation. Anaerobic digestion is a three-phase process with sequential biochemical reactions of hydrolysis, acidification, and methanation. Complex organic molecules such as cellulose, starch, proteins, and lipids are first hydrolyzed by mixed populations of non-methanogenic bacteria into simpler soluble molecules such as glucose, peptides, amino acids, and long chain fatty acids. The extracellular metabolic end products are primarily short chain fatty acids such as acetic, propionic and butyric acids, aldehydes, alcohols, hydrogen, and carbon dioxide. These serve as substrates for the growth of methanogenic populations of bacteria, which in turn generate their own extracellular end products, primarily methane and carbon dioxide.

The anaerobic digestion of organic wastes is thus mediated by two distinct groups of bacterial populations, which differ from each other in growth characteristics and sensitivity to environmental conditions. There is evidence that the methane producers are more sensitive to changes in temperature and pH than the acid producers, and that the rate limiting step in the process is the rate of formation of methane from the volatile fatty acids. For example, the loading rate of a well mixed, mesophilic digester is restricted to avoid the accumulation of volatile fatty acids in excess of 5.9 $kg/m^3/day$ or else the resulting drop in pH inhibits growth of the methanogenic bacteria. This limitation makes it necessary to operate digesters at long retention times, thereby increasing the size and, thus, capital and operating costs.

Separating the acidogenic and methanogenic populations of bacteria and permitting them to grow in separate reactors under environmental and nutritional conditons most suitable for each group, may optimize the process. Recent studies of two-phase anaerobic digestion have been encouraging (Ghosh and Klass, 1977). The maximum conversion of glucose to methane was found to require four hrs for the acid-phase and four days for the methane-phase digestion. The conversion of cellulose to methane was found to require more time, namely one to two days for the hydrolysis and acid-phase digestion and five to eight days for the methane-phase digestion. Production rates and yields of methane were found to exceed those for conventional, single-phase digesters. Thus, phase separation may be expected to provide substantial benefits including reduced digester volume and reduced costs of construction.

Problems

Some serious problems must be solved before acceptance of the use of digesters in combination with small livestock operations can be expected. One problem is the integration between the availability of the gas and the energy needs of the farming enterprise. The quantity of available gas may be expected to vary dramatically during the year as well as from year to year. Progressing through the year, the activity on the farm may range from having very few or only young animals present to a fully stocked herd of marketable animals. The quantity and quality of manure available for digestion vary correspondingly. More importantly, it may be advantageous to have no pigs at all during certain years. The fluctuating level of availability poses limitations on the uses which can be made of the gas. These problems are mediated in part by making the use of straw an important part of the process.

The energy needs of many applications vary during the year and so does the availability of the gas. The situation where energy needs and gas availability are equal will be a fortuitous circumstance which never may occur unless special operating procedures are carefully worked out and strictly adhered to. The use of the gas may be enhanced by converting it to an energy form which can be stored more easily. Better continuity also may be achieved by feeding the digester with materials other than manure. Much of the straw left on fields presents a readily available source of such materials.

An important research need is the development of management systems specifically aimed at the full utilization of all resources available to the farmer. We suggest that problems to be investigated include those of finding means to store the gas for later use, transformation of the gas to a form of energy which can be stored and transported, the development of uses for the gas which lead to products that can easily be sold by the farmer, increase of gas production through the addition of cellulosic waste products, and, finally, improvement in the digestion process itself.

Summary

Tables 1 and 2 show the combustible energy content of the products involved in raising pigs from 50 to 100 kg. The values are for a one-year period. In Table 2, comparisons have been made. Energy values of the products are shown as percent of the total energy input, including the solar energy fixed by the grain and straw and the energy expended in the farming operations.

The nutrients in the manure represent energy that was expended in the mining and processing. Each time these nutrients are returned to the land, the equivalent amount of energy does not have to be expended and, therefore, is saved. The production of N, P, and K requires 17,600, 3,200, and 2,200 kcal/kg, respectively. The use of the minerals represents a saving of 25×10^6, 1×10^6, and 1×10^6 kcal/yr.

Interpretation of the data with respect to efficiency of energy use must be done with care. The efficiency of energy use is defined as the energy content of the product divided by the energy expended to produce the product. Difficulties arise when the energy inputs are not clearly defined. For example, the input of 108 units of cultural energy produces 894 units of energy in the form of grain and straw. The energy efficiency of farming, therefore, is 8.3 or 830%. On the other hand, the energy input of 619 units produces 59 units of pork for an energy efficiency of 0.09 or 9%. Discussions of energy efficiency easily can lead to misunderstanding and certainly to gross misrepresentation of facts.

The most significant conclusion of our analysis is that digestion of the manure can produce substantial amounts of energy. With straw added to the digester, the energy content of the biogas is 86.4% of the energy used on the farm for all farming activities. This is clear indication that the potential exists to develop methods of operation which allow farms to become energy independent.

PART II: PROTEIN

Methane and Yeast or Microfungi

Introduction

In part I of this report, we reported on the use of manure to produce biogas. The discussion included descriptions of the composition of the feed and the manure. Energy balances and materials balances were presented. Here we report a management system which emphasizes the recovery of protein by growing yeast, microfungi, or algae in the liquid phase of the manure (Figure 2). Reference will be made to information presented in Part I.

Organic matter dissolved in the liquid phase of the fresh manure may be used as a substrate for the growth of yeast or microfungi. These organisms convert the organic matter into cell mass. Harvesting of the cell mass leaves an effluent which still contains nutrients and minerals for the growth of algae. The effluent also may be used on land for its fertilizer value. The harvested biomass can be fed to the pigs as a protein supplement in their diet.

Process Description

For this discussion we assume that a gutter flushing system is used to remove the manure from the animal quarters. Flushing at the rate of 140 l/h dilutes the 300 l of manure to a volume of 3,660 l/day (Figure 2). Other rates of flushing may be chosen according to local needs. The diluted manure is collected in a sedimentation pit where the solids are separated from the liquids by settling. The solids are pumped into an anaerobic digester. The liquids overflow into a holding tank from which they are pumped to a fermentation vessel. The holding tank provides temporary storage so flow to the fermenter can be regulated and allows additional sedimentation. The liquid remaining after harvesting the yeast cells contains most of the dissolved minerals in the manure. This effluent can be used as a fertilizer or as a substrate for the growth of algae. The effluent from the digester may be added to that from the fermenter and used in the same manner.

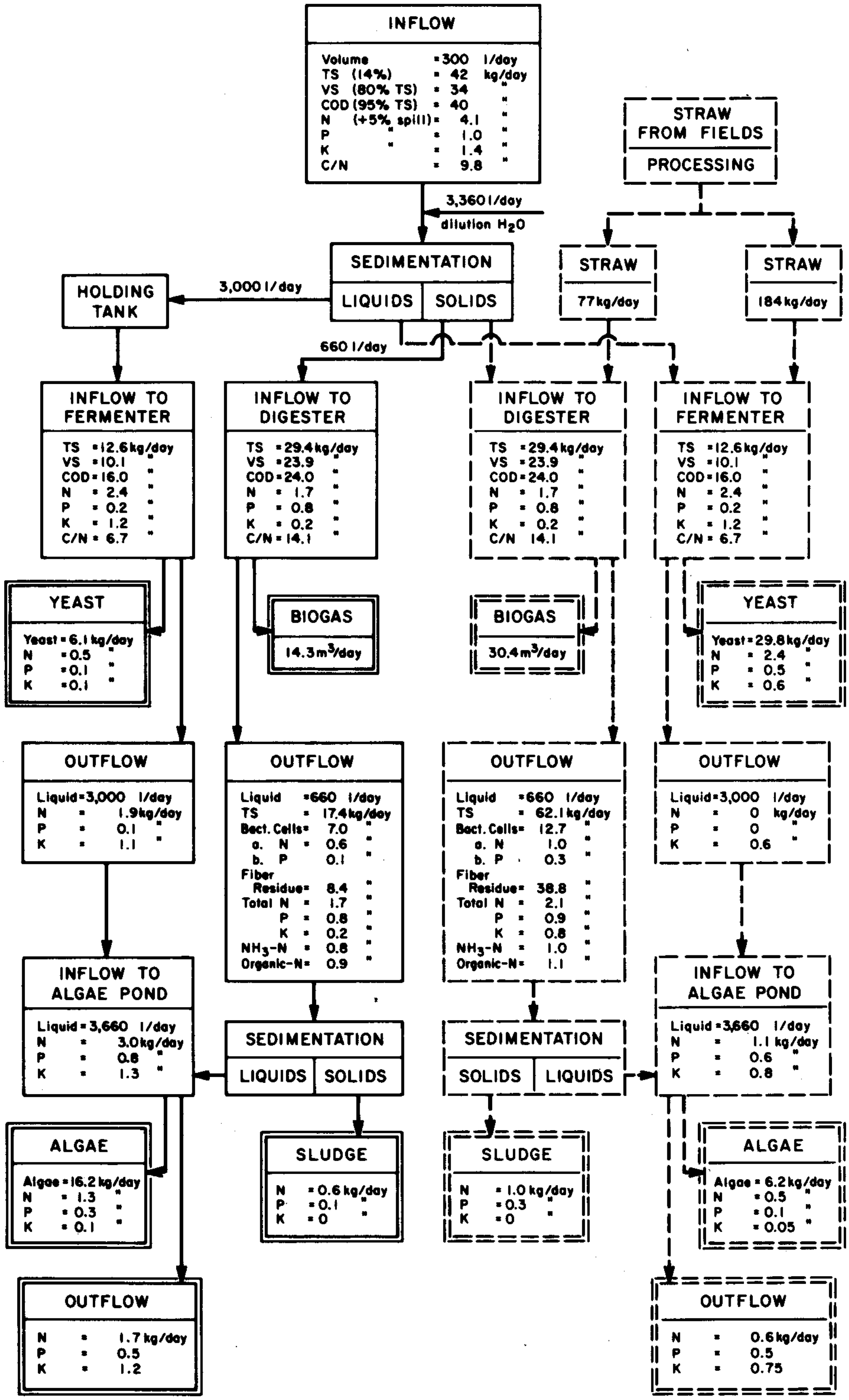

Figure 2. Material balances for the manure discharged by 100 pigs being fed to gain weight from 50 to 100 kg at the rate of 0.8 kg/day. The solids are digested and the liquids are used as a substrate for yeast. Similar balances are shown for a system of management where straw is added to the digester and fermenter.

Fermenter

A conceptual model of the culture of yeast in the liquid phase of swine manure may be based on recent developments in fermentation technology and the culture of single cell organisms (Forss et al., 1974; Humphrey, 1974; Meyrath, 1975).

It is assumed that 3,000 l of diluted manure are supplied to the fermenter each day in a continuous flow (Figure 1). Conventional processes of yeast manufacture require a retention time of three to five hrs. At a retention time of five hrs, the volume of the fermenter must be 625 l (3000 l/h x 5/24). To allow for the expansion of the substrate from gassing and foaming, the volume of the fermenter should be increased to about 2,000 l. The substrate has a COD of 16 kg/day and contains 2.4 kg N/day. We shall assume that only N in the ammonium form is readily assimilated by the yeast or microfungi.

If all of the COD is attributed to organic carbon that can be assimilated by the organisms, then a theoretical yield of 0.38 g of cells/g of COD is possible (Sykes, 1975). The expected yield, therefore, is 6.1 kg cell matter/day (16 kg COD/day x 0.38 kg biomass/kg COD). In general, the N content of the yeast ranges from 8 to 10% of the dry matter so that about 0.5 kg N/day are removed, corresponding to a yield of 3.1 kg of crude protein per day (N x 6.25), which is equivalent to 34% of the amount of protein supplied by soybeans and 8.5% of the total protein requirement.

Addition of Carbon Source

The unused ammonium N, namely 2.4 - 0.5 = 1.9 kg/day, also can be converted into yeast or fungal protein by adding organic carbon. Such a procedure has advantages over supplying the excess N to outdoor ponds for algal growth. The growth of yeast and fungi does not depend on solar radiation, and growth rates are much faster than for algae. The culture of yeast and fungi requires less space than the culture of algae in outdoor ponds. Also, better control over the quality of the product can be exercised.

Assuming that yeast cells contain 8% N by weight, the excess N of 1.9 kg/day could be converted to 23.75 kg of yeast (1.9 kg N/0.08).

Additional COD is required to accomplish this. This can be supplied by properly pretreated cellulosic wastes such as straw. Using the yield of 0.38 kg of cells/kg COD, the requirement is 23.7/0.38 = 62.5 kg COD. This could be supplied by 58.6 kg of sugars (62.5 kg COD/1.067 kg O_2 per kg sugar = 58.6 kg sugar).

The sugars may be obtained by the hydrolysis of straw. Assume that the straw contains 64% (w/w) cellulose and hemicellulose and that 50% is converted to sugars. One kg of straw then yields 1.0 x 0.64 x 0.50 = 0.32 kg of sugar. The amount of straw to be hydrolyzed is therefore 184 kg/day. The fermenter receives 16 + 62.5 = 78.5 kg of COD and the yield of yeast cells is 29.8 kg/day with a protein content of 50% by weight (78.5 kg COD x 0.38 kg cells per kg COD). The protein yield of 14.9 kg/day is 164% of that supplied by soybeans and 41% of the total requirement for protein.

After removing the yeast cells, the effluent contains no solids, some N and P, and about 1.0 kg K/day. The actual amount of minerals in the effluent depends on the chemical composition of the yeast or microfungi. The efficient use of assimilable sugars and nitrogen depends on the rate at which oxygen can be supplied to the growing cells. Technical limitations to efficient oxygen transfer to the yeast or microfungi have not been overcome.

The feasibility of converting all the nitrogen in the liquid phase of the manure to protein depends on finding solutions to technical problems including the hydrolysis of the straw and fermentation and on finding reliable sources for a continued supply of suitable waste products.

Back-feeding

The proposed scheme for the recovery of yeast or microfungal protein from swine waste involves returning some of the harvested biomass slurry, with a high concentration of cells, to the main fermentation vessel (Figure 3). The added cells increase the rate at which the substrate can be broken down. As a consequence, the rate at which raw material is added can be increased. Back-feeding increases the yield per unit of fermenter volume for a substrate low in organic matter.

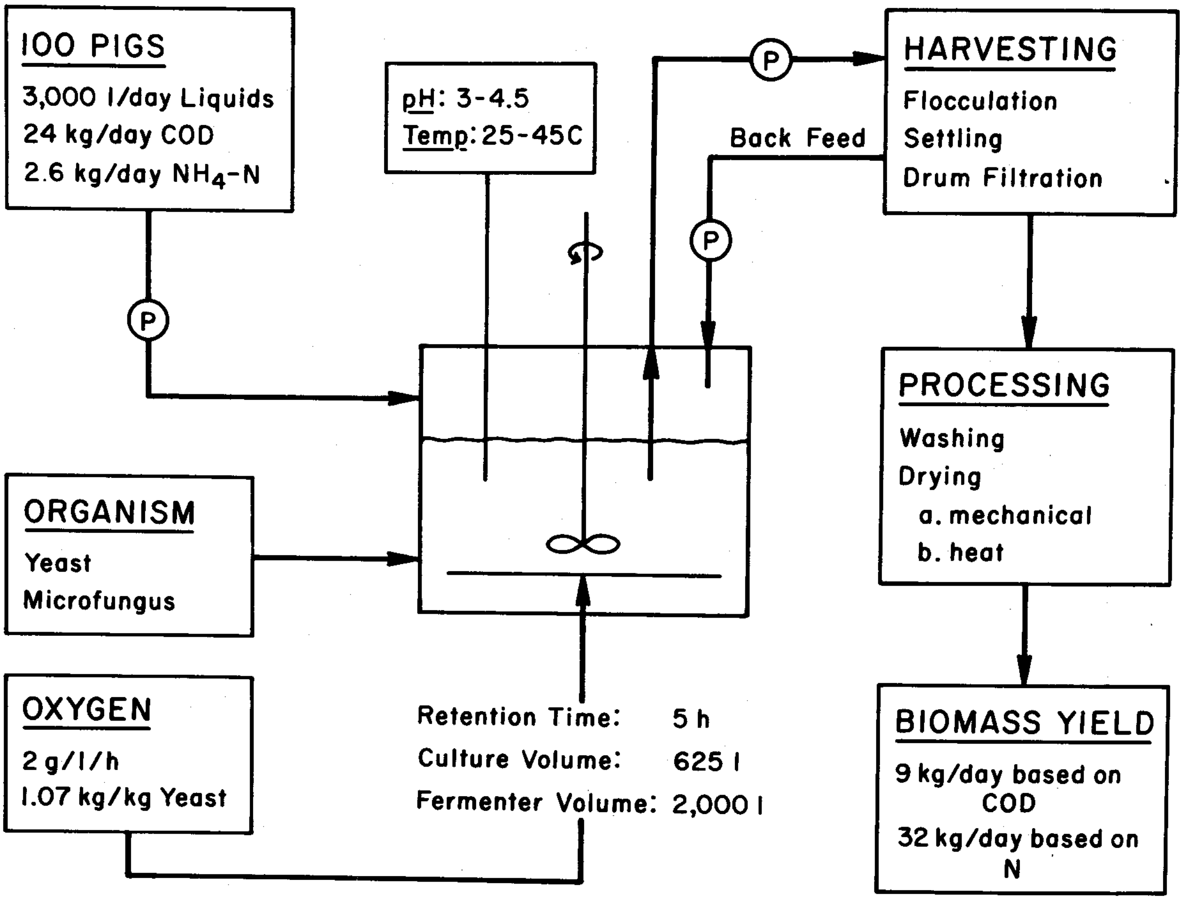

Figure 3. Flow chart for the recovery of yeast and microfungi from the liquid phase of swine manure.

The possibility of decreasing the retention time through back-feeding means that the size of the fermentation vessel can be reduced. To treat the 3,000 l of waste water per day at the conventional retention time of five hrs, one-fifth of the 625 l of culture volume inside the fermentation vessel must be replaced every hour. This corresponds to a dilution rate of 0.2/h. A dilution rate of 1.0/h, made possible through back-feeding, means that the culture volume can be reduced from 625 l to 125 l. The total volume of the fermentation vessel, allowing for expansion by gassing and foaming, would then be 400 l instead of 2,000 l.

Selection of Organism

Selection of either yeasts or microfungi depends on several considerations. Among these are the possible need for sterilization of the waste water to favor growth of the organism of choice, the need to minimize cooling costs, and problems of harvesting. The need for sterilization might be eliminated by using an organism which can tolerate hydrogen ion concentrations in the range of pH 3 to 4.5. Bacterial growth is greatly reduced or eliminated at this acidity.

Harvesting can be done by centrifugation, aggregation, or flocculation. Of these, centrifugation is the most expensive method. The preferred organism should have a strong tendency to aggregate or flocculate to facilitate harvesting by gravitational sedimentation or by filtration. Furthermore, the organism should be able to tolerate elevated temperatures of 40 to 45 C to reduce cooling costs. Yeast strains with these desired properties have been isolated (Meyrath, 1975). Some are available from the American Type Culture Collection, such as *Candida acidothermophilum* (ATCC No. 20381).

We propose use of the microfungus *Paecilomyces varioti*. This organism is being used successfully in Finland to produce the so-called "PEKILO" protein from sulfite liquor at pulp mills (Forss et al., 1974). A 10,000 ton/year plant has been built by United Paper Mills, Ltd., at Jämsänkoski in central Finland and has been in operation since 1974. The PEKILO protein is sold as an ingredient in animal feedstuff for calves, pigs, and poultry.

Paecilomyces varioti has several distinct advantages over the *Candida* or *Torula* yeast conventionally grown on sulfite liquor. Its crude protein content is in the range of 55 to 60%, whereas that of the *Candida* yeast is from 45 to 50%. By virtue of its mycelial structure, the microfungus can be harvested by drum filtration while the small cell size of the *Candida* yeast requires centrifugal separation, which is much more expensive and energy intensive. The use of strains of yeast with the strong ability to flocculate (Meyrath, 1975) could negate this advantage of the microfungus by allowing the harvesting of yeast by gravity settling. The microfungus has the further advantage that its fibrous nature allows the removal of large amounts of water by mechanical pressing to a solids content of 30 to 40%. This feature is of economic importance because mechanical dewatering is much cheaper than drying entirely by heat which is necessary for the yeast.

Cooling Requirements

The growth of yeast releases about 4,000 kcal/kg of dry matter. The indicated yield of 29.8 kg/day generates 119,200 kcal which can raise the temperature of 3,000 l of diluted waste by 39.7 C. Some of this heat is needed to raise the temperature of the inflow to the fermentation vessel. The temperature of the liquid waste in the holding tank depends on the local climate. At our location, the temperature of the waste water was as low as 5 C in the winter and as high as 25 C in the summer (Boersma et al., 1978). To raise the temperature of the inflow from 5 C to 45 C would require 120,000 kcal/day. Thus, cooling would be minimal during the winter months. At 25 C, only 60,000 kcal/day would be required for heating the inflow. Cooling, therefore, would be necessary during the summer. Consideration should be given to the possibility of heating the inflow to the digester so this heating requirement is eliminated.

Anaerobic Digester

Management of the anaerobic digester was discussed in detail in part I. Yields are lower here because part of the COD is transferred to the fermenter. Yields of 14.3 m^3 biogas/day without the addition of cellulosic waste and 30.4 m^3/day with the addition of cellulosic waste are indicated. We have not discussed uses for the gas here, but suggest that a useful application would be the processing of the single cell protein.

Use of Effluents

Effluent streams from the digester and from the fermenter are available for further use. They can be used separately or in combination. We assume the mixing of the two outflow streams. When spread on land, the 3,660 l/day provide a depth of water of 0.0366 cm per ha per day. Spreading the outflow from 10 days on 1 ha provides 0.37 cm of water and 30 kg N, 8 kg P, and 13 kg K. If all the water were supplied to the 15.26 ha needed to raise the grain, they would receive 0.84 cm of water per year and 68.8 kg N, 18 kg P and 29.8 kg K.

Distribution of water can only be done during the growing season. The storage requirement for 200 days would be 732 m^3, equivalent to a reservoir three m deep with a floor area measuring 12.2 x 20 m.

Algae

Introduction

Dissolved nutrients in the liquid phase of the manure also can be recovered by photoautotrophic organisms such as algae. The manure stream can be managed in two ways to accomplish this. Effluents from the digester and/or the fermenter can be used as a substrate for algae or the fresh manure can be separated into solid and liquid fractions to be used separately for anaerobic digestion and as a substrate for algae, respectively. The second method omits the use of the liquid phase for the growth of yeast in the fermenter but makes it available for algal growth.

Recovery of Nutrients by Photoautotrophs

High levels of radiant energy and temperatures in the range of 25 to 35 C are desirable for maximum rates of growth of algae. Radiation intensity decreases rapidly with culture depth, even in clear solutions. The liquid phase of swine manure is far from clear. It contains color compounds in addition to suspended solids. Furthermore, the presence of dissolved organic matter supports the rapid growth of bacteria indigenous to the waste. All these limitations to light penetration can be overcome in part by dilution with large volumes of water.

The surface area required for the daily volume of diluted waste is determined by the depth of the culture, the retention time, and the total volume. The depth is determined by the radiation intensity. At high levels of radiation, the depth can be greater than at low levels.

The retention time is determined by the rate at which algae grow and, therefore, depends on day length, radiation intensity, and temperature. The cultures can be deeper and the retention times shorter during the summer than during the winter. For a daily inflow of 3,660 l, a depth of 15 cm, and a retention time of four days the surface area would be 97.6 m^2. For a depth of 10 cm and a retention time of eight days, the surface area would be 8 x 3,660 x 0.001/0.10 = 292.8 m^2.

It may be advisable to limit the culture of algae to the summer in geographic regions with a short day length and low levels of solar radiation during the winter. The substrate could be stored for later use. A decision on whether to do so must be based on a comparison of the cost of storage with the cost of building and operating the larger pond.

We considered two methods of management, one where the effluent from the digester is used and one where the liquid phase of the manure is used.

Use of Digester Effluent - Fermenter Not Used

The entire flow of fresh manure is routed to the anaerobic digester. The effluent from the digester is clarified in a storage tank by allowing settling to occur. The clarified liquid is used as a substrate for algae. The rate of outflow from the digester and the concentration of nutrients in it were described in Part I. The effluent does not need further dilution, because soluble organic compounds have been removed. Adequate growth of algae is expected at a culture depth of 15 cm and a retention time of 8 days. The required surface area would be 48 m^2 for a daily volume of 900 l. This volume results when 600 l/day of dilution water are used instead of the 300 l/day indicated in Figure 1, Part I.

The digester effluent contains 4.1 kg total N, 50% of which is present in the form of NH_3-N and readily assimilated by algae. We measured assimilation of 30 to 50% of the N by algae under field conditions (Boersma et al., 1978). This percentage can be increased by proper management. The effluent is expected to yield (4.1 x 0.50) x 0.50 x 6.25 = 6.2 kg protein per day when no straw is added to the digester. With straw added, the outflow contains 5.2 kg N/day and the expected yield is 8.1 kg protein per day. Assuming a protein content of 50%, the corresponding yields of algal dry matter are 12.5 and 16.2 kg/day. The yields may be greater than indicated, if the organic-N present in the digester effluent is converted to NH_3-N by bacterial ammonification.

The protein yields correspond to 68% and 89% of the protein supplied by the soybeans and to 17% and 22% of the total protein requirement. These comparisons must be revised downward by allowing for the poor digestibility of the algal cells.

Use of Fermenter and Digester Effluents

With the fermenter included in the management system, the combined outflows from fermenter and digester contain 3.0 and 1.1 kg N/day with and without the addition of straw, respectively. The yields of algal protein, assuming all the N to be in a form which is readily assimilated, and a utilization rate of 43%, are (3.0 x 0.43) x 0.50 x 6.25 = 8.1 and 1.1 x 0.50 x 6.25 = 3.1 kg/day. The total yields of protein from fermenter and digester are 3.1 + 8.1 = 11.2 and 14.9 + 3.1 = 18.0 kg/day corresponding to 123.1% and 197.8% of the protein supplied by the soybeans or 30.7% and 49.3% of the total requirement for protein.

Use of the Liquid Phase

When the liquid phase of fresh manure is used as a substrate for algal growth, it becomes important to suppress the growth of bacteria. These grow readily because of the high concentration of dissolved organic matter. Adequate penetration of light and suppression of bacterial growth are achieved by dilution. We found that a 50 fold dilution of the 300 l of liquid manure discharged by the pigs assured stable cultures of algae. Because of the need for large volumes of water, flushing is the most logical means for manure transport.

The manure stream is managed as described previously where the liquid phase was routed to a fermenter. The liquid from the sedimentation pit must be diluted about 50-fold to make it suitable for the culture of algae. The flush water provides about 3,000 l per day so that the liquid leaving the sedimentation pit must be mixed with about 12,000 l of water before it can be pumped into the algal pond. The pond, therefore, receives a total of about 15,000 l of liquid waste per day. The 12,000 liters of dilution water have to be provided only once as fresh water. Thereafter, the waste water from the pond is available for reuse as flush water and dilution water after the algae have been harvested.

Loss of water from evaporation requires make-up water. The rate of evaporation depends on local climatic conditions and on the temperature of pond water. Requirements for fresh make-up water can be substantial when the surface area is large.

The liquid phase of the manure with the effluent from the digester added contains 3.2 kg NH_3-N without straw added to the digester and 3.4 kg with straw added. The expected protein yields are 10 and 10.6 kg/day, respectively. This system of management has several serious disadvantages (Boersma et al., 1978). These include the instability of the cultures, the large ponds required, the need for large volumes of water, and problems with bacterial growth. They combine to result in a high cost per unit product and the need for highly developed management skills. The system seems to be less advisable than the use of fermenters.

Harvesting of Algae

Algae may be separated from water by centrifugation or chemical flocculation. Centrifugation on a small scale can be done with yeast separators such as the model YEB 1334A manufactured by the Alpha-DeLaval Co. of Poughkeepsie, New York. This separator has a maximum feed rate of 1,000 l/h and a 0.55 kW motor. At 600 l/h, the centrifuge removes at least 95% of the biomass, including bacteria. At a dry matter concentration of 1 g/l and a flow rate of 600 l/h, the energy consumption would be 0.96 kWh/kg. At $0.05/kWh, the harvesting cost would be $0.05/kg dry matter or $0.10/kg protein, assuming a crude protein content of 50% (w/w).

One of the most efficient and reliable methods of harvesting microalgae is by chemical flocculation with coagulants such as aluminum sulfate (alum), aluminum chloride, ferric sulfate, lime, and organic polyelectrolytes. This method is expensive and the product is contaminated with the coagulating chemical. Its use as a feed supplement in livestock rations is questionable because of possible toxicity effects and reduced digestibility and palatability.

The least expensive but also the least efficient methods of harvesting algae are sedimentation, autoflocculation, and filtration through microstrainers. The efficiency of microstrainers could be improved significantly by growing filamentous algae instead of single-cell or colonial algae and by increasing the concentration of the filamentous algae. Selecting filamentous algae to decrease the cost of harvesting has disadvantages. Filamentous algae most often are blue-green algae, many of which produce toxins lethal to both man and animal. Strict operational controls as well as product quality controls, therefore, must be maintained to ensure the safe use of the final product as a feed supplement in livestock rations. Furthermore, the filamentous algae require longer retention times than single-cell algae because of the difference in their rates of growth. The filamentous algae, therefore, require a correspondingly larger surface/land area to treat the same volume of waste water each day.

Summary

Tables 3 and 4 show combustible energy content of products involved in raising pigs from 50 to 100 kg. Values shown are for a one-year period with pigs being fed during 350 days. Protein consumption by the pigs and protein recovery from waste products are also shown.

The tabulations shown here in combination with those of Part I indicate that the yield of biogas is reduced by inclusion of the fermenter. However, as a result, substantial quantities of protein can be produced. The relative advantages cannot be judged without comparing costs and benefits. These comparisons have not been made. Conclusions depend on the relative costs of energy and protein.

Because difficulties are involved with algae production, not the least of which is the cost of production facilities, we favor the management scheme where straw is used in fermenter as well as digester, and growth of algae is not attempted.

Methane and Bacteria

Recovery of useful products from the manure also can be accomplished by emphasizing the growth of bacteria in aerated basins. Manure is

Table 3. Energy values of several products used and produced on a farm where pigs are raised from 50 to 100 kg. There are 100 pigs at all times.

Products	Energy Content
	10^6 kcal/yr
NO STRAW	
pork (19,600 kg/yr)	59
yeast (2,135 kg/yr)	10
algae (5,906 kg/yr)	35
biogas (5,005 m^3/yr)	27
nitrogen (787 kg/yr)	14
WITH STRAW	
pork (19,600 kg/yr)	59
yeast (10,430 kg/yr)	50
algae (2,187 kg/yr)	13
biogas (10,640 m^3/yr)	57
nitrogen (560 kg/yr)	10

Table 4. Energy inputs and outputs for the system of management shown in Figure 2. The numbers shown pertain to a period of one year.

Category		No straw			With straw		
		Energy	% of total input	Protein	Energy	% of total input	Protein
		10^6 kcal	%	kg	10^6 kcal	%	kg
ENERGY INPUT							
corn grain		447	72.2	9,590	447	43.2	9,590
soy beans		32	5.2	3,185	32	3.1	3,185
straw for digester		--	--		126	12.2	
straw for fermenter		--	--		290	28.0	
farming:							
fuel & electr.	54.2						
fertilizer	32.5						
labor & machinery	21.7						
livestock maint.	24.0						
feed processing	8.0						
	140.4	140	22.6		140	13.5	
		619	100.0	12,775	1,035	100.0	12,775
ENERGY OUTPUT, USEFUL PRODUCTS							
pork		59	9.5		59	5.7	
yeast		10	1.6	1,085	50	4.8	5,439
algae		35	5.6	2,835	13	1.3	1,132
biogas		27	4.4		59	5.7	
N		14	2.3		10	1.0	
sludge		--	--				
		145	23.4	3,920	191	18.5	6,571
OTHER ENERGY SINKS							
heat loss from pigs		254	41.0		254	24.5	
CO_2 and other gases		130	21.0		410	39.6	
other (e.g. fiber residue)		90	14.5		180	17.4	
		474	76.5		844	81.5	

routed by gutter flushing to a tank for separation of solids and liquids. The liquid fraction containing only particles smaller than 35 μm in length is pumped to an aerated basin. The remaining solids and associated liquids are pumped to an anaerobic digester. The liquid outflow from the digester also is added to the aerated basin after gravity settling to remove solids. Digested solids and associated liquids are stored for use as fertilizer.

Aeration Basins

Aeration basins are operated to maximize the production of bacterial solids from the liquid waste. A much shorter retention time than used in conventional waste treatment systems is required which means that less oxygen and energy is needed. The basin is operated at optimum solids concentration by returning a portion of the bacterial solids to it. The effluent from the basin flows to a solid-liquid separator for harvesting the bacterial biomass. To harvest the solids, a filter which retains particles longer than 5-10 μm and gravity settling may be used. The liquid removed from the separator is recycled for use as flush water in the system. The harvested solids are removed as a slurry to be added to the feed supply. This slurry is expected to contain about 4% solids (w/w) of which about 60% (w/w) are bacterial cells. These cells are expected to contain approximately 60 to 75% protein.

The slurry of bacterial cells is mixed with the dry feed ingredients to eliminate the need for drying. Thus, a liquid feeding system for the pigs is necessary. The total volume of slurry plus feed is expected to equal the daily requirement for water and dry feed combined.

Bacterial cell protein is a relatively high quality protein for swine feed. Some research has been done on feeding such slurries from oxidation ditches to the animals that produce the waste. No disease problems have been noted to date.

Product Yields

The production of bacterial protein in the aeration basin probably will be limited by the BOD_5 supplied to it. Total BOD_5 available ranges from 8 to 16 kg/day. Excess N enters the aeration basin, but the loss of ammonia N during the aeration process is expected to bring the system to an equilibrium level. The aeration basin should be operated to produce about 0.6 kg of suspended solids (micro-organisms) per kg of BOD_5 added. This requires a retention time of approximately 6 h and a theoretical volume of about 850 liters. The volume should be doubled to allow for foaming and overload. The energy required for aeration would be about 750 kcal/kg BOD_5 based on 1.5 kg O_2/kg BOD_5 added.

The suspended solids are expected to be nearly all bacterial cells with a protein content of about 77%. The protein produced per day would be 3.7 to 7.4 kg/day (8.0 to 16 kg of BOD_5/day x 0.6 kg of SS/kg BOD_5 x 0.77). The bacterial protein could replace from 41 to 81% of the protein provided by the soybean meal supplement.

The digester function and yield would be as described earlier. The gas from the digester can be used to run a generator to supply electricity to the aerators of the basin. Waste heat from the generator could be used to heat the digester.

PART III: OPTIONS FOR THE MANAGEMENT OF SWINE MANURE

This report has described the flow of energy and materials through two systems which can be used for the biological recovery of nutrients and energy from swine manure. Other pathways are possible and some will be discussed briefly. The descriptions cannot be used to make final choices about the relative merits of each of the methods. Those choices require information about factors which are not discussed here, such as costs, manageability by the farmer, and reliability of the biological systems. Information about these factors can be obtained only by additional research and development.

We described how the liquid waste first may be used as a substrate for the growth of selected heterotrophs such as yeast and/or microfungi. The heterotrophs grow independently of light so the liquid phase of the manure can remain highly concentrated. This pretreatment method eliminates the need for large volumes of dilution water and removes the turbidity from the waste water following separation of the yeast or microfungi. This process increases the availability of light when the waste water is used subsequently for the growth of algae. The algal pond, therefore, can be made small in this mode of operation.

The most serious reservation about the culture of algae is the harvesting problem. The use of a fish polyculture can be considered as an alternative to harvesting the algae by centrifugation. This procedure also avoids the cost of processing the algae to improve the low digestibility of the protein and the low availability of lysine. Fish are easy to harvest and present a source of high-quality protein which has been accepted as a livestock feed supplement.

Several biological conversion processes can be arranged into systems or options to manage swine waste. These options are combined in an architectural perspective shown in Figure 4. A plan view of the arrangement is shown in Figure 5. These two diagrams combine several options. The first option is one designed to produce biogas and use the digester effluent as a fertilizer. A refinement of this option involves the growing of algae in the digester effluent. In this operation, the manure is digested to produce gas and to solubilize plant nutrients.

The nutrients in the liquid phase of the digested manure are recovered by algae. The option described in Part II of this report includes the digestion of solids to produce gas while yeast and microfungi are cultivated in the liquid phase of the manure. It is also possible to produce biogas and use the digester effluent as a source of nutrients for fish.

To complete the evaluation of these concepts of nutrients and energy recovery from animal wastes and to broaden the base of knowledge of the systems approach to animal waste management, much additional research and development work is necessary.

The recovery of useful end products is limited by the availability of nitrogen and organic carbon in the manure. Substantial improvements in the yields of single-cell protein and biogas could be realized by the addition of organic carbon from cellulosic wastes such as crop residues. Research emphasis should be on solutions to the technical difficulties of converting cellulosic wastes into carbon which can be assimilated readily by microorganisms.

The relative merits of each method of bioconversion should be analyzed with respect to economic feasibility, manageability by the farmer, and reliability.

Feeding trials should be carried out to evaluate the value of the product obtained from the bioconversion systems.

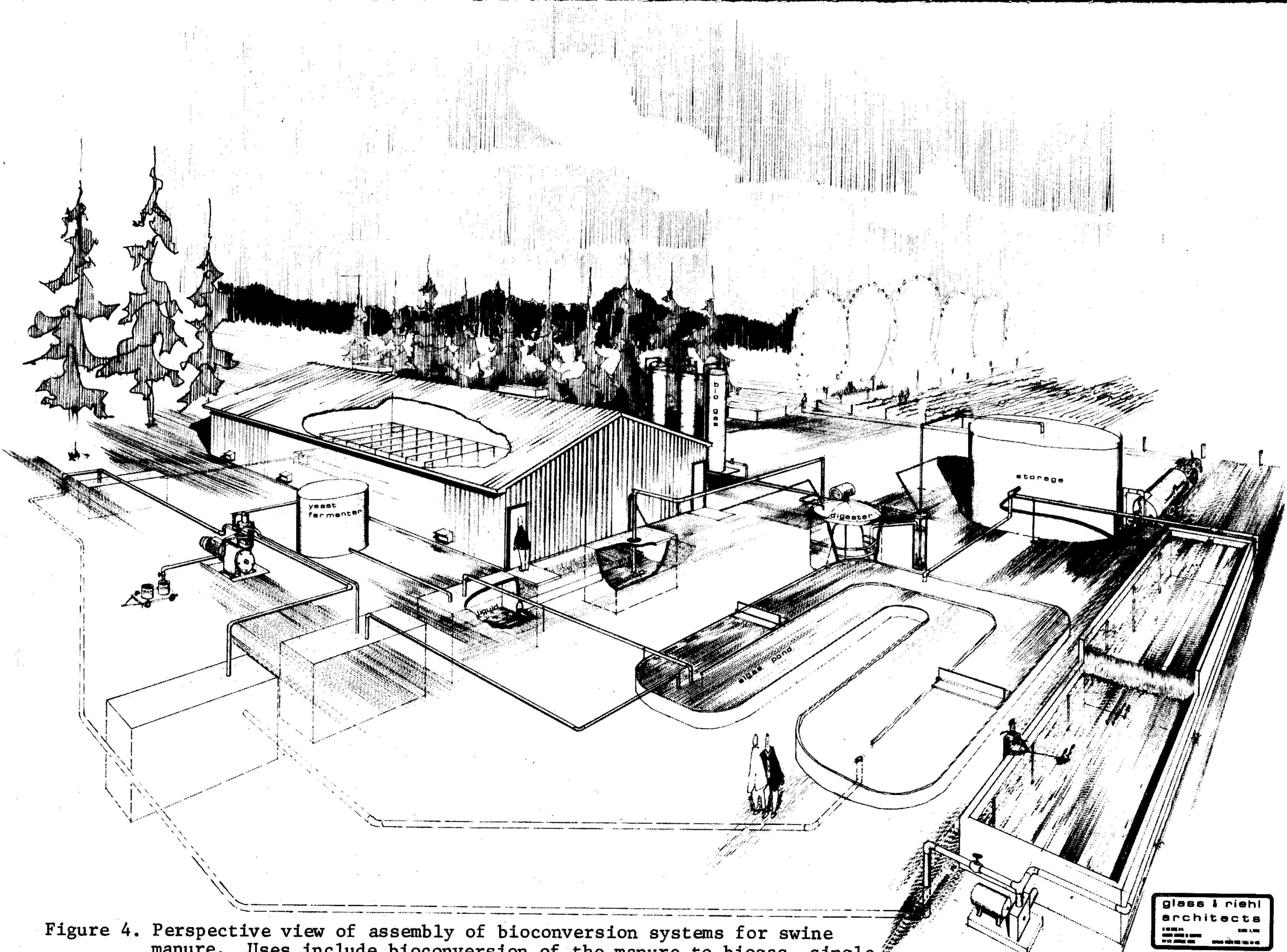

Figure 4. Perspective view of assembly of bioconversion systems for swine manure. Uses include bioconversion of the manure to biogas, single cell protein (algae, yeasts and microfungi), and fish protein.

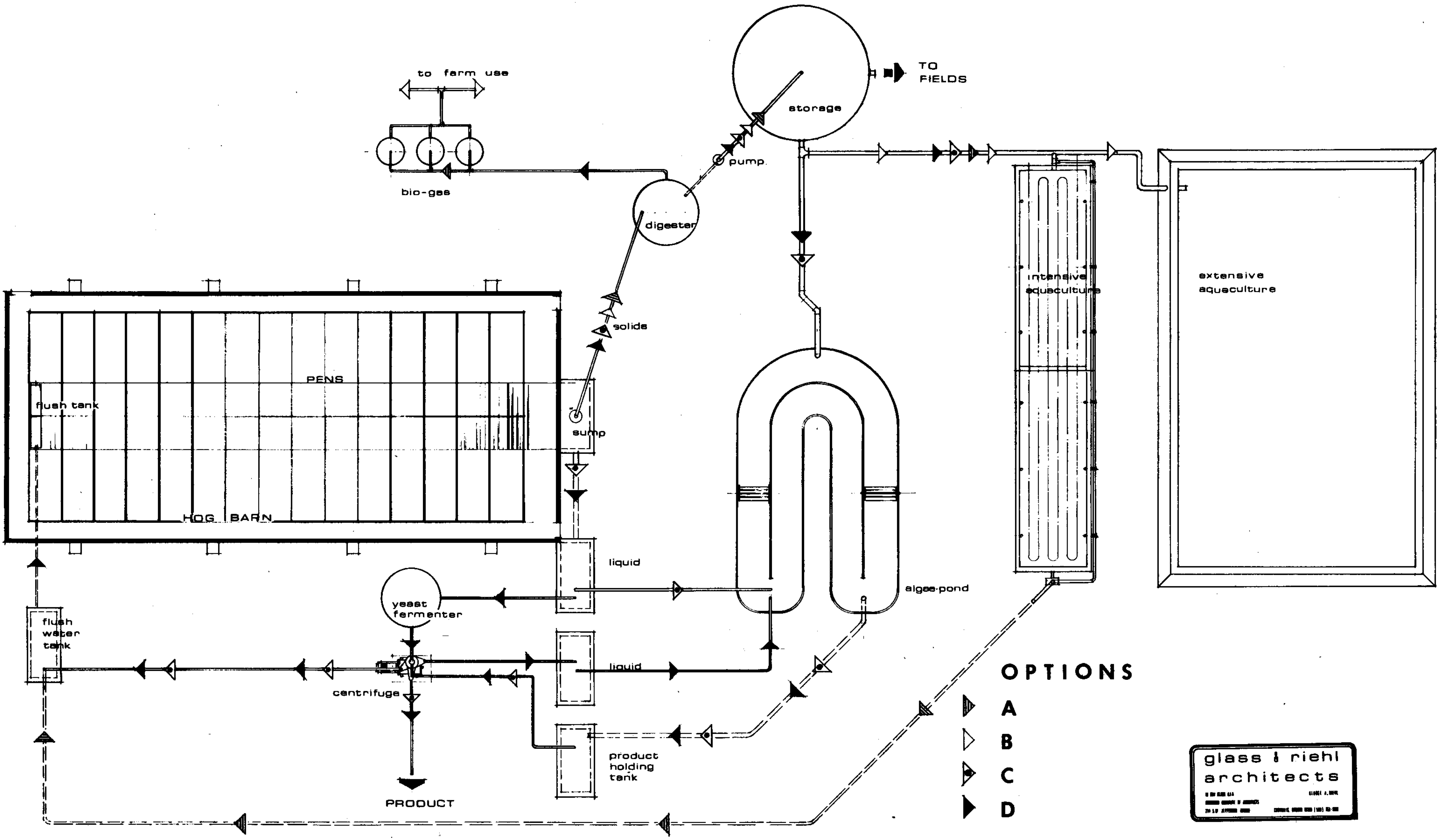

Figure 5. Plan view of the components shown in Figure 4.

PART IV: RECOMMENDATIONS

Methods for the recovery of energy and protein from swine manure through bioconversion have been discussed. It was noted in the introduction that the energy and material balances presented have not been achieved under operating conditions. To realize the indicated levels of energy and protein recovery, much additional research remains to be done. Brief comments about needed research follow.

Economic analyses of several alternative farming systems, designed specifically for maximum use of waste products through recovery of energy and nutrient sources for livestock feed, should be performed. The ultimate success of technological development of systems to obtain energy and feed depends on the economic viability of each compared to other alternatives for the utilization of these resources. Economic feasibility of alternative nutrient recovery and energy generation systems should be analyzed. This involves the study of critical variables affecting economic feasibility with future projections of feasibility as changes occur in the ratios of energy prices to other prices. Cost-to-benefit analyses based on comprehensive analyses of the alternative systems should be performed.

Whereas, economic feasibility is important, no less important is manageability by the farmer and reliability of the system of choice in terms of biological stability. The most promising systems, therefore, must be tested under field conditions.

The recovery of useful end products is limited by the availability of nitrogen and organic carbon in the manure. Substantial improvements in the yield of single-cell protein and biogas could be realized by the addition of organic carbon to the manure from cellulose containing waste materials, such as crop residues. Emphasis should be on research to solve the technical difficulties involved in converting the cellulose into readily-assimilable carbon. Pretreatment of these wastes is necessary to liberate the bound cellulose from hemicellulose and lignin and to maximize the availability of monomeric sugars.

Fermentation methods to be used for converting organic and inorganic materials suspended or dissolved in the liquid phase of the manure by growing yeast or microfungi should be studied in detail. To increase the yield of microbial protein, these studies should include the addition of cellulosic waste materials.

Methods to enhance biogas production by digestion of manure should be studied further. For example, the potential of two-phase anaerobic digestion to improve production rates and yields of methane should be investigated. Phase separation may provide substantial benefits, including reduced digester volume, reduced installation costs, and reduced operating costs. The C/N ratio of swine manure is about 10. Yield of biogas with the maximum energy content is higher at the C/N ratio of about 30. Cellulose containing waste products should be studied as digested additives. Pretreatment of these wastes to liberate the bound cellulose from hemicellulose and lignin and to maximize availability of monomeric sugars will be necessary.

Additional assessment of the nutritional value of all products of bioconversion is necessary. Tests should involve assessment of digestibility, protein quality, in the case of proteinaceous materials, through amino acid analysis, biological value, and protein efficiency ratio and replacement value for presently used feedstuffs. Toxicological evaluations should be made in long-term trials with histological examination of the tissues. It would be useful to conduct multi-generation feeding trials.

Growing algae using runoff from the fermenter and/or digester as a substrate remains uncertain. The culture of algae should be studied in further detail. The concept of selecting green algae or blue green algae by adjusting the retention time and recycling a portion of the harvested algae to the growth reactor should be tested under field conditions. Furthermore, processing methods should be developed to improve the digestibility of the algae and the availability of the lysine.

Alternative methods not covered in this report should be considered. A promising method might be the recovery of protein from swine manure using a polyculture of fish and the continuous culturing of bacteria, yeast, or microfungi.

PART V: LITERATURE CITED

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