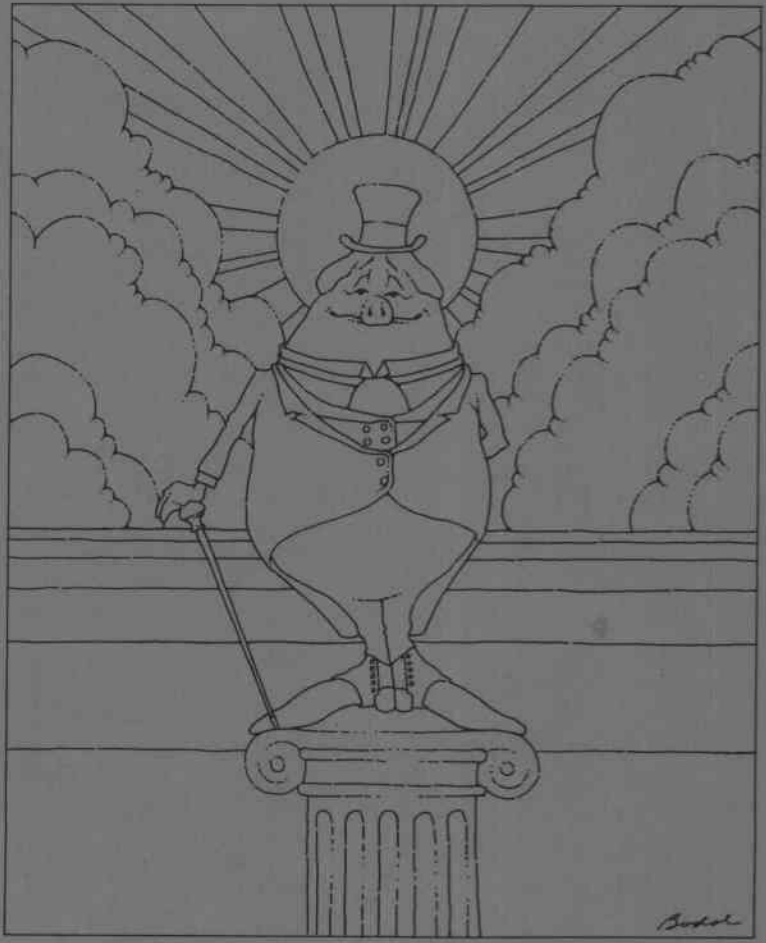
Management of Swine Manure for the Recovery of Protein and Biogas



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FINAL REPORT

MANAGEMENT OF SWINE MANURE FOR THE RECOVERY OF PROTEIN AND BIOGAS

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ABSTRACT

Major findings of an investigation into the concept of nutrient and energy recovery from a swine waste management system are reported. Algae and bacteria were used to convert swine manure into methane-rich fuel gas and supplemental protein for animal feed. Waste heat from electricity generating plants was simulated to test its value in enhancing the biological recovery of nutrients and energy.

The experimental facility was built adjacent to the Swine Research Center at Oregon State University and consisted of animal quarters with solid concrete floor and gutter to house 50 pigs, an anaerobic digester with a volume of 14 m^3, and 12 outdoor algae basins with a combined surface area of 24 m^2 and a combined volume of 6,000 l.

Manure was removed from the animal quarters by a gutter flushing system. The solids were separated from the liquids by gravity settling and then pumped into the digester for solubilization and recovery of biogas. The liquid phase of the diluted manure was pumped into the outdoor basins to serve as nutrient substrate for the growth of the high temperature strain 211/8K of *Chlorella vulgaris* as the predominant algal species. The algal biomass was concentrated by centrifugation and freeze dried. Its nutritional value as a protein source was determined by feeding trials with Long-Evans rats.

Pretreatment of the manure by a 50-fold dilution with water was found necessary before the liquid phase was suitable for algal growth. When the manure was not sufficiently diluted, the high concentration of organic matter promoted bacterial growth over algal growth.

Chlorella vulgaris 211/8K was found to require a monthly average of the daily rate of solar radiation in excess of 2,000 kcal/m^2 day and a photoperiod of at least 11 h in order to maintain a sufficiently high concentration of cells for harvesting at retention times of 8 days or less.

The highest concentration of 0.70 g/l of algae was obtained at the culture depth of 10 cm, the retention time of 6 days, and the temperature of 35 C. Increasing the culture depth to 20 cm reduced the concentration of algae by 50 percent. However, the total biomass remained nearly the same at either depth.

Culture depth, temperature, retention time, and rates of solar radiation affected the percentage of contribution made by *Chlorella* to the total biomass. Essentially all of the biomass consisted of algae when the culture depth was no more than 10 cm, the temperature 30 to 35 C, the retention time not less than 6 days, and the rate of solar radiation in excess of 2,000 kcal/m^2 day.

Maximum yields of 10 to 12 g/m^2 day of algal dry matter were obtained. *Chlorella* converted 1 to 2 percent of the total solar radiation into chemical energy. When the quantity of algal dry matter recovered from the waste was related to the live weight of the animals which produced the waste, maximum yields of 2 to 3 g/kg pig per day were obtained.

The nitrogen balance in the outdoor basins showed that 21 to 47 percent of the nitrogen available to the algae in the form of ammonium N was converted to harvested biomass. The

biomass contained 6 to 11 percent N on a dry matter basis. The low percentage of conversion of ammonium N into organic N was attributed to the daily variations in the intensity of the solar radiation and the fluctuations in the pH and dissolved oxygen concentration of the cultures, induced by the photosynthetic activity of the algae.

Continuous mixing, at least during daylight hours, was found to be essential for maintaining a predominant and competitive population of *Chlorella.* However, the loss of cultural stability due to the invasion of predators, fungi, and undesirable species of algae remains unpredictable until research determines which factors enable *Chlorella,* or any other chosen alga, to maintain predominance. Continuous mixing and control of pH are but two such factors. A third factor may be the recycling of a portion of the harvested algae to increase the concentration of *Chlorella* in the basins.

Freeze-dried algae had a low protein efficiency ratio (PER) of 0.84 which improved to 1.31 by steam autoclaving for 30 min at 120 C. The digestibility of the algae was 59 percent which improved to 68 percent after autoclaving. When used as a protein supplement to corn at a dietary level of 18 percent, the algal protein performed as well as fish and soybean meal at a dietary level of 13 percent. Amino acid supplementation of a corn diet containing autoclaved algae indicated that lysine was the first-limiting amino acid while methionine was present in adequate quantities. Development of processing methods to increase the protein digestibility and the availability of lysine are needed before the algae can be used successfully as a replacement for soybean meal in swine rations.

The recovery of nutrients from swine waste by bacteria would best be accomplished in a continuous culture system. Yields of 0.38 g cells/g COD and yields of 2.2 g cells/kg pig per day appear feasible.

The anaerobic digestion of the manure solids removed 55 percent of the total solids. The destruction of the volatile solids was 56 percent, and the COD was reduced by 41 percent. The daily gas production averaged 1.06 m^3/kg VS removed. The gas contained 68 percent v/v CH_4 and 32 percent v/v CO_2.

The necessity to dilute the swine waste with large volumes of water in order to make the liquid phase of the manure suitable for algal growth, and the potentially high cost of harvesting and processing the algae, prompted the consideration of other management systems for the recovery of nutrients and energy from swine manure, including the culturing of yeast, microfungi, and fish. Architectural perspectives and plan views were developed for each management system together with schematic diagrams showing the flow of energy and materials through each system, based on the feed and energy needs and the waste discharge of 100 pigs.

CONCLUSIONS

Based on the findings of this investigation, the following may be concluded:

1. To recover nutrients from swine waste by algal biomass production in outdoor basins, it is necessary to dilute the fresh manure about 50-fold before the liquid phase becomes suitable for algal growth. The dilution is necessary to reduce turbidity and the concentration of organic matter which otherwise will favor the growth of bacteria over the growth of algae.

2. Pretreatment of the manure with large volumes of dilution water is not likely to be practical for a system of swine waste management with nutrient recovery because:

    a. large-volume pumps and storage tanks as well as extensive areas of land for algal growth ponds are required to treat the daily volume of waste,

    b. the algal biomass has to be concentrated from large volumes of waste water with a corresponding increase in cost,

    c. a large volume of stock culture of *Chlorella* has to be maintained and a large volume of *Chlorella* inoculum has to be prepared in case of failure of the algal recovery unit(s),

    d. it is uncertain whether *Chlorella* is able to compete successfully in large ponds against unwanted species of algae, and

    e. water may be a limiting resource.

3. Biological methods of pretreatment which reduce the need for dilution to a minimum include anaerobic digestion and continuous culturing of yeast or microfungi in the liquid phase of the manure. The heterotrophs remove organic carbon from the waste to produce single cell protein, but leave sufficient nitrogen and minerals for the subsequent growth of algae.

4. Rather than attempt to introduce a preselected alga from the laboratory into outdoor basins, it may be more practical and less costly to control the predominance of mixed populations of either green or blue-green algae which occur naturally by manipulating operational parameters such as retention time. For example, treatment ponds with continuous flow-through of waste water usually contain mixed populations of algae. At short retention times, single-celled and colonial type green algae predominate over slower growing, filamentous blue-green algae. By recycling a portion of the harvested algae to the pond, the concentration of the green algae could be increased to assure predominance and enhanced recovery of nutrients from the waste.

5. Green algae are preferred over blue-green algae because they are not known to produce substances which are toxic to livestock. Furthermore, given a fixed volume of waste which needs to be treated each day, the filamentous blue-green algae require more surface/land area for growth than the unicellular green algae because of the difference in the rates of growth.

6. Control of the pH between 7.5 and 7.9, preferably by the injection of CO_2, is essential to maximize CO_2 fixation and protein synthesis, prevent the loss of ammonium N by volatilization, prevent the precipitation of micro- and macro-nutrients essential for algal growth, and prevent the loss of cultural stability due to autoflocculation.

7. Year-round operation of a nutrient recovery system utilizing algae will depend primarily on the prevailing rates of solar radiation. When the daily rate of solar radiation remains at less than 2,000 kcal/m^2 day for extended periods of time, the growth of algae under field conditions is reduced to such an extent that the retention time has to be measured in weeks rather than days. It is then necessary to expand the surface area in order to treat the same volume of daily waste. Maintaining a constant temperature of 30 to 35 C does not compensate for the reduction in algal growth due to the limited availability of light. The year-round operation of algae basins does not seem practical for most parts of the U.S. except Florida, the Southwest, southern California, and other selected areas which receive yearly averages of daily rates of solar radiation in excess of about 4,000 kcal/m^2 day.

8. The seasonal variability in the intensity of solar radiation requires adjustments in culture depth and retention time in order to maintain algal growth at a maximum rate.

9. If the waste pumped into the algae basins contains sufficient organic carbon to support bacterial growth, then the contribution made by the algae to the total biomass varies with the intensity of solar radiation, culture depth, temperature, and retention time. To maintain an end product which consists mostly of algae therefore requires close monitoring of algal growth and control over operational parameters.

10. The operation of a large scale nutrient recovery system could be simplified by first pretreating the waste to remove organic carbon and to minimize bacterial growth, and by maintaining a constant culture depth of 10 to 20 cm and a constant retention time of 6 to 8 days. A daily rate of solar radiation of at least 2,000 kcal/m^2 day should be available to the algae. This intensity of radiation would be present from April through September for most of the U.S. The nutrient recovery system would be shut down during the remainder of the year and the manure stored.

RECOMMENDATIONS

To complete the evaluation of the concept of nutrient recovery from animal wastes and to broaden the knowledge base in the systems approach to animal waste management, the following research is recommended:

1. 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.

2. Processing methods should be developed to improve the digestibility of the algae and the availability of lysine.

3. 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 and capital cost requirements.

4. Alternative methods of nutrient and energy recovery from swine waste should be investigated, including the polyculture of fish and the continuous culturing of bacteria, yeast, or microfungi.

5. 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. Emphasis should be placed on research to solve the technical difficulties of converting cellulosic wastes into readily assimilable carbon.

6. The relative merits of each bioconversion method should be analyzed by establishing balances of energy and materials through each system. The cost, manageability by the farmer, and reliability of the most promising system should be tested under field conditions.

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UTILIZATION OF WASTE HEAT IN A SYSTEM FOR MANAGEMENT OF ANIMAL RESIDUALS TO RECOVER AND RECYCLE NUTRIENTS

INTRODUCTION

Concept of Project

The consumptive use of non-renewable natural resources and the environmental degradation resulting from pollution have become of major concern. The exponential increase of the world's population, now doubling every 36 years, places unprecedented demands on natural resources and on conventional methods of food production. The finite supply of oil and natural gas, the present lack of alternate sources of low cost energy for an energy dependent society, and the need to produce more food every year for a rapidly increasing world population make it vitally important that we conserve energy resources and develop unconventional methods of food production.

At Oregon State University, one approach used for energy conservation and creation of new food sources is the development of integrated systems in which the waste products from one industry become the raw materials for another. In particular, attempts are being made to integrate waste management and food production techniques utilizing waste heat from power generating plants.

In the power generating and livestock industries large quantities of energy and nutrients are being wasted as unwanted by-products. Technologies have been developed to dispose of these byproducts in order to reduce their detrimental effects on the quality of air, land, and water. On the other hand, growing shortages of energy as well as protein for both human consumption and animal production are now anticipated during the coming decades (AAAS, 1974; 1975). As a consequence, increasing attention must be directed to the development of beneficial uses for these by-products.

Availability of Waste Heat

Rate of Electrical Energy Production

Waste heat is an integral part of the production and the use of electrical energy. In establishing the scope of the problem, it is important to obtain an estimate of current and future rates of waste heat production. This estimate must be based on a judgement of the desirable output of the U.S. economy. The consumption of all energy sources as well as the use of electrical energy provides an estimate of economic welfare and growth (Starr, 1975). Growth in total energy consumption has roughly paralleled the growth of the gross national product during this century (Figure 1). This is so because all our productive activities require energy. Even the preparation of food for the dinner table is a process that depends heavily on external energy input, in addition to that supplied by solar radiation.

Figure 2 shows the energy used in the form of electricity as a function of the gross national product. While total energy consumption grew at about the same rate as the gross national product, the energy used as electricity grew at a rate about 2.5 times that of the total

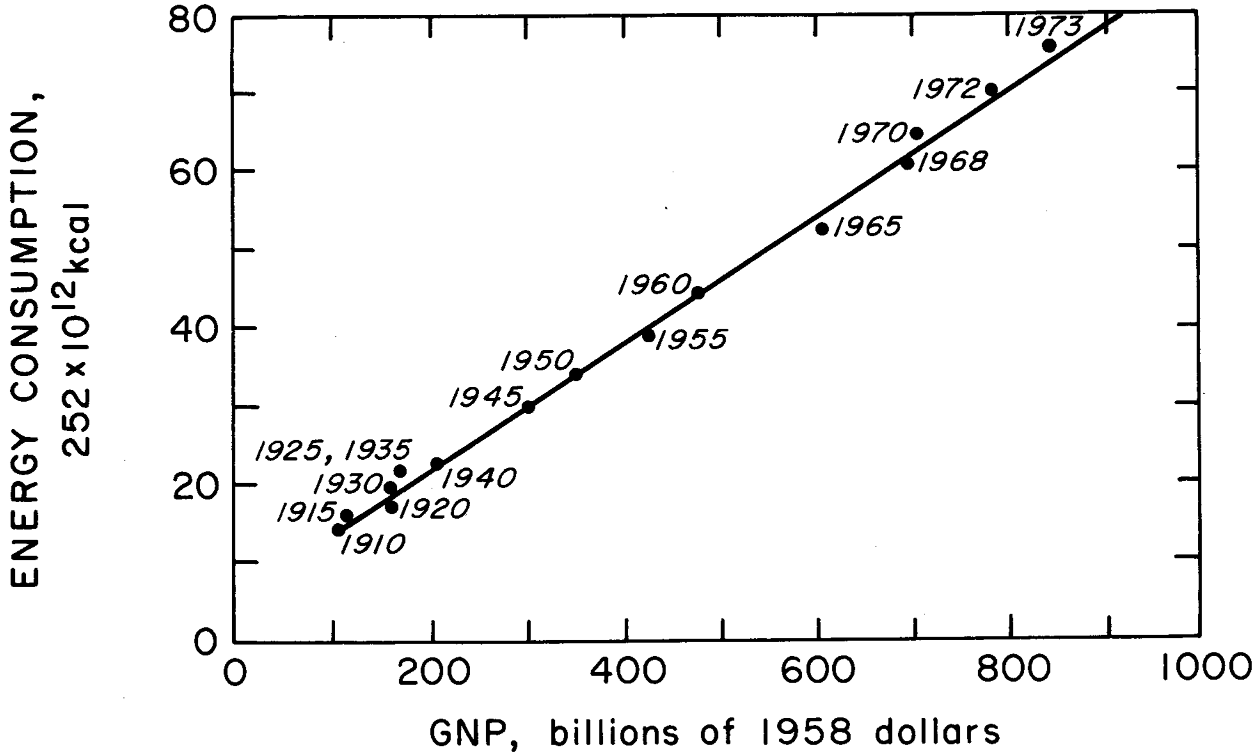

Figure 1. Total energy consumption per year in the United States as a function of gross national product during the period 1910-1974. (After Starr, 1975).

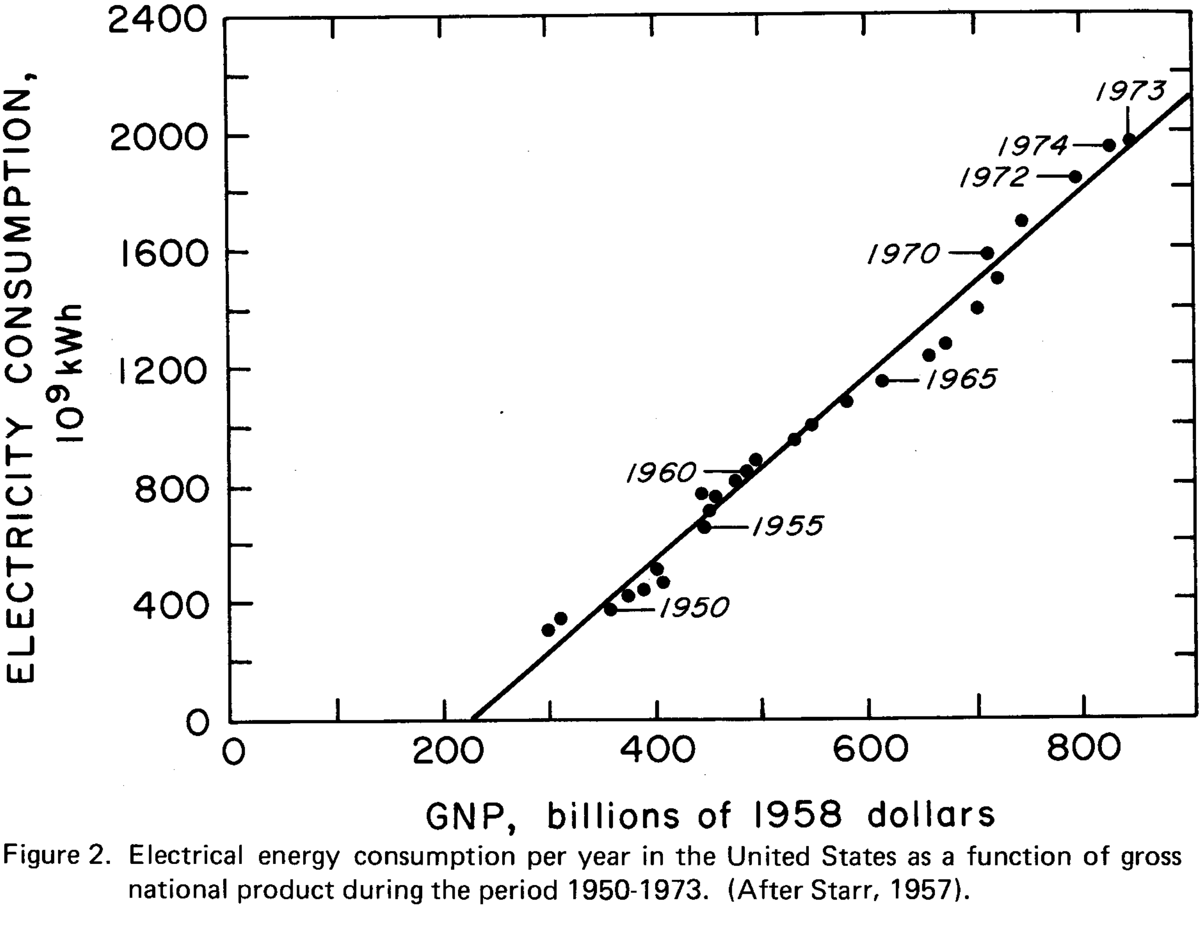

Figure 2. Electrical energy consumption per year in the United States as a function of gross national product during the period 1950-1973. (After Starr, 1957).

energy, indicating that historically electricity has been substituted for other forms of energy. This development might be expected to accelerate because of the convenience in use, distribution, and safety of electricity. A further impetus to this development is the uncertainty concerning future availability of oil and gas, as well as the future cost of these commodities. These uncertainties may be expected to motivate users of these fuels to shift to electricity wherever possible.

Alternative Energy Sources

Application of advanced concepts of energy supply can make only a limited contribution to the supply of energy during the next 25 years (Starr, 1975). Research and development uncertainties are great. This applies to the use of fusion processes as well as to the use of solar energy and geothermal energy. No working systems based on these advanced concepts exist. A continuing series of scientific and engineering difficulties must therefore be expected. Any of these might be so unusual or difficult to overcome that it could delay the development of the new option. Furthermore, research and development efforts require long lead times to reach a commercial stage.

It is therefore not realistic to expect new energy concepts to play an important role in the immediate future. Electricity, much of it generated by nuclear power plants or coal fired plants, must provide the energy needed during the next 25 years.

Thermodynamic Efficiency

Thermodynamic considerations control the efficiency with which the heat source can be converted to power. The efficiency of conversion exerts a strong influence on fuel utilization and reject heat produced. The U.S. power system operates with an efficiency between 30 and 35 percent. At 35 percent, the ratio of waste heat to electrical power produced is about 1.85 and at 45 percent it is 1.20. The ratio would be decreased to 0.67 at an efficiency of 60 percent. The projected energy conversion efficiencies of a variety of power generating systems are shown in Table 1.

Table 1. Electric power sources for the future and projected energy conversion efficiencies. (After Dieckamp, 1971).

Source	Operating experience	Conversion efficiency
	Years	%
Fossil fuel	60	35-40
Light water reactor	15	30-33
Fast breeder reactor	5	40-43
Metal magnetohydrodynamics	Research	45-50
Plasma magnetohydrodynamics	Development	50-55
Fusion	Basic Research	30-80

The amount of waste heat decreases as the temperature of the conversion process increases. For example, liquid metal MHD converters, operating at temperatures of about 870 C, in conjunction with a steam cycle, can increase the energy conversion efficiency to about 45 or 50 percent. This corresponds to increasing the useful energy available from existing energy resources about 20 percent (Dieckamp, 1971).

Table 2 shows an estimate of the anticipated growth in generating capacity in the U.S. until 2020 (Krenkel and Parker, 1969). The information shown for the rate of production of waste heat was developed by the authors of this report by assuming operating efficiencies ranging from 34 percent at the present time to 61 percent by the year 2020. The rate of production of warm water will continue to rise throughout this period. Note that in the year 2020 some individual facilities must operate at efficiencies greater than 61 percent because at that time many of the less efficient stations will still be in use. These calculations indicate that while efficiency may rise from 30 to 60 percent, the total amount of waste heat released continues to grow.

The availability of the waste heat for useful purposes depends on power plant design and type of cooling system used. Figure 3 shows annual temperature profiles for condenser cooling water for a cooling tower and for a cooling pond. It is apparent that the waste heat is of low quality, ranging in temperature from 15 to 50 C, and therefore of little value in most industrial processes. But it can be useful for certain urban needs such as space heating of schools, office complexes, hospitals, and shopping centers. It is also ideally suited to support biological systems whose productivities are temperature dependent, such as agriculture, aquaculture, and the production of single cell protein by algae and yeast. Other uses of the waste heat have been proposed and described (Knudsen et al., 1975).

Food Production Problems

Rates of Food Production

Agricultural productivity has increased throughout the past decades, and this is indeed fortunate, as the demand for food has similarly risen due to population increases and the increased level of affluence. Some recent publications, however, have predicted rather dire consequences in the not-too-distant future (Meadows et al., 1972; Meadows et al., 1974). Based on an exponentially increasing population and a gradually decreasing amount of land available for growing crops due to the use of prime agricultural land for other purposes, these authors concluded that by the year 2000 the amount of arable land available will just be sufficient to feed the world population (Figure 4). These are global estimates, assuming agricultural productivity to remain at its 1970 level. Even if the yield per hectare is increased to four times the 1970 level, which would be quite an accomplishment in itself, we would again face the same problem by the year 2050. This study points out the need to increase productivity and to do it soon. Other studies have reached similar conclusions (Pimentel et al., 1975).

Energy Use in Agriculture

The goal of simply increasing productivity can have serious consequences. Much of modern agriculture depends on the availability of low cost fuel. The "green revolution"

Table 2. Projected generating capacity and rates of waste heat production in calories per year (cal/yr) obtained by assuming the indicated operating efficiencies. (After Krenkel and Parker, 1969).

Year	Projected generating capacity	Projected operating efficiency	Rate of waste heat production
	10^{18} cal/yr	%	10^{18} cal/yr
1970	1.11	34	0.73
1980	2.27	37	1.43
1990	4.24	41	2.50
2000	7.20	46	3.89
2010	10.99	53	5.16
2020	16.28	61	6.35

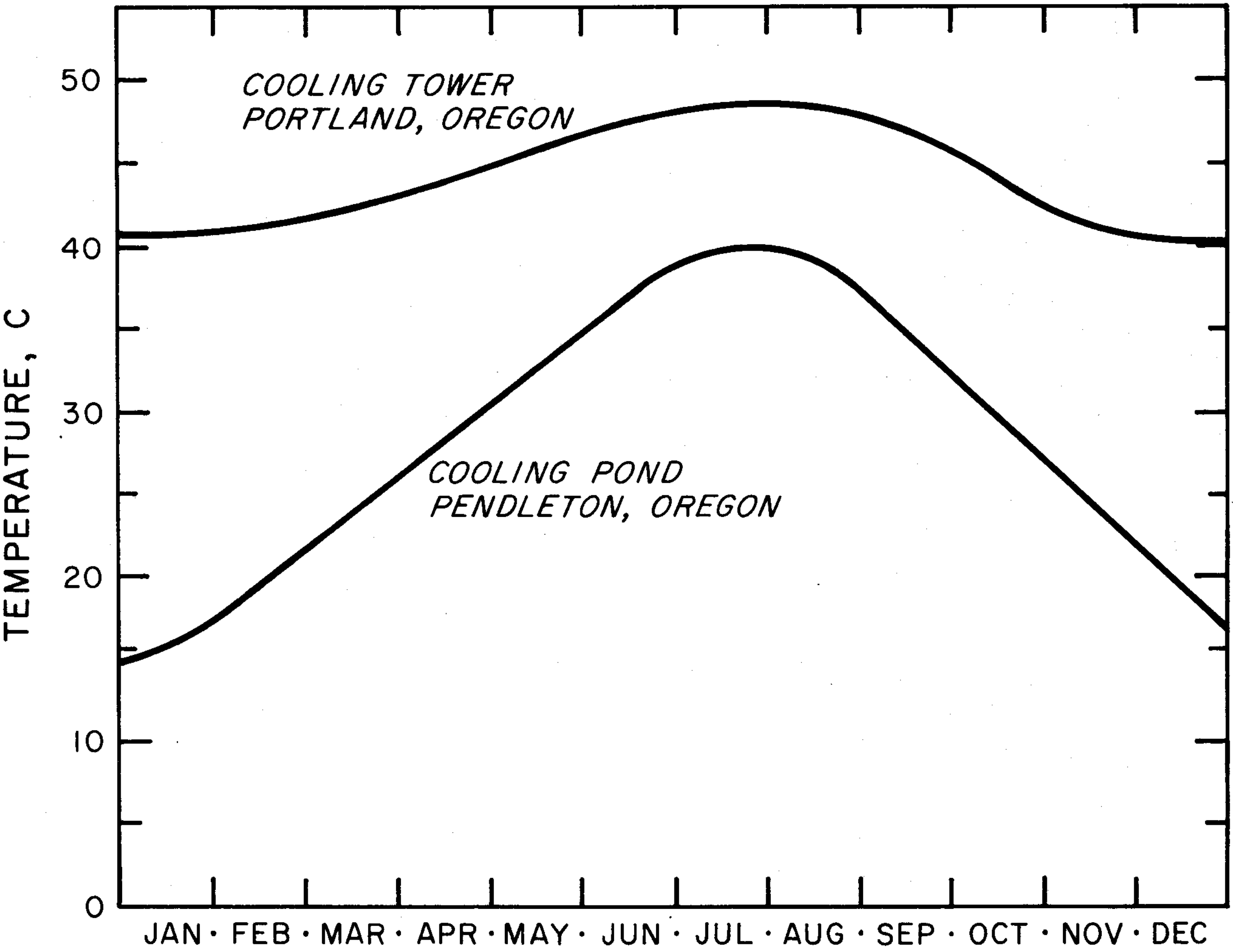

Figure 3. Annual temperature profiles of condenser cooling water at the point of discharge using a cooling tower for a location near Portland, Oregon, and a cooling pond for a location near Pendleton, Oregon (Boersma et al., 1974).

mainly consisted of introducing high yielding plant varieties and mechanical farming methods. These high yielding varieties require large fertilizer inputs, which in turn require large energy inputs. With the spectre of increased energy costs in the future, the possible effects of food production are alarming.

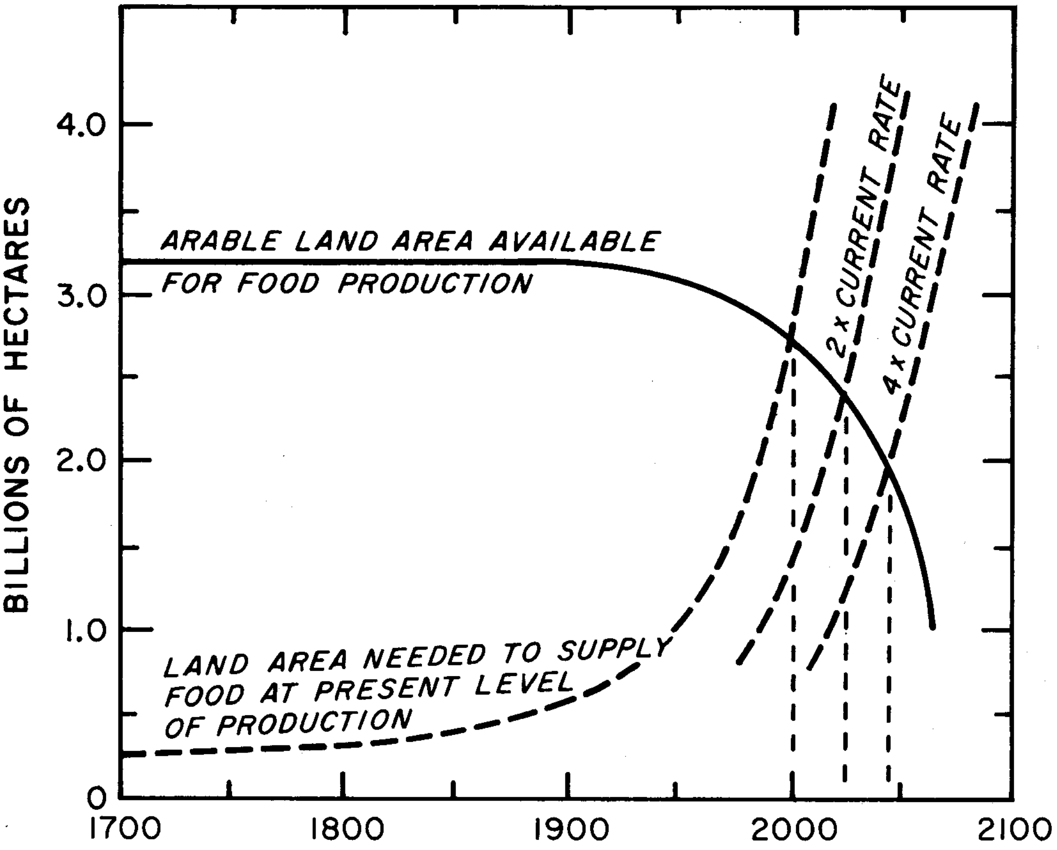

Figure 4. Arable land area available for food production as a function of time compared with the land area needed for adequate food supplies. The broken line shows the land area needed to supply a basic food ration to the world population assuming current yield levels. The rate of increase shown is based on projected rates of growth of the number of people living at the different times. The solid line shows the land area available in the world for food production. The decrease in available area of arable land is based on projected use of this land for highways, airports, and other non-agricultural uses. At some time in the future the number of hectares required to produce the food will become equal to the number of hectares available to grow it on. The occurrence of this date can be postponed by increasing the yields per hectare as indicated by the lines "two times current rate" and "four times current rate." (After Meadows et al., 1972).

Several attempts have been made to quantify energy flows in agriculture. Table 3 shows the total annual per capita energy consumption for food related activities in the United States for the year 1974 (Federal Energy Administration, 1975). The 14.9 Mkcal/person year is about 16 percent of all energy used (Figure 1). It indicates that energy required on the farm was only about 18 percent of all energy needs of the food system in 1974. Other reports show a lower requirement for energy use in the food production system.

A similar analysis was made for Australia (Anonymous, 1974). Results (Table 4) show a lower rate of energy consumption (6.3 vs. 14.9 Mkcal/person year) but a similar distribution of use. About the same percentage was used for on farm production, but the Australian study showed a lower percentage for processing and distribution. The differences are in part due to different types of agriculture considered.

A recent publication (Farm Electrification Council, 1975) estimates food related activities to consume a little over 11 percent of total U.S. energy consumption. The total energy consumption was estimated to be 90 Mkcal/person year (Starr, 1975), so that the energy required for food related activities would be approximately 10 Mkcal/person year. This estimate is in good agreement with many recent estimates although somewhat lower than those made by the FEA. Uses in categories were: on farm production, 18 percent; processing, 33 percent; wholesale-retail, 16 percent; transportation, 3 percent; and home preparation, 30 percent. The marketing process (transportation-wholesale-retail) used slightly more energy than was required for on-farm production. In the area of food processing and marketing, the trend has been toward more processed food requiring more handling and transportation. Frozen, canned, and dehydrated foods are becoming increasingly important. Households consumed about 30 percent of the food related energy. Refrigeration and freezing are the most important single uses, followed closely by cooling.

One way to consider the efficiency of energy use in agriculture is to compare the food related energy expenditures with the food energy consumed. The present rate of food consumption in the U.S. provides a diet of 1,380 kcal/person day of animal products and 2,015 kcal/person day of plant products (Heichel and Frink, 1975). This is equivalent to 1.24 Mkcal/person year. Thus, to provide 1.24 Mkcal/person year in the form of food energy, about 10.0 Mkcal/person year of energy input are required. According to this estimate 8.0 kcal of fossil fuel are required to produce 1.0 kcal of food energy.

A detailed estimate made by Nelson et al. (1975) of the flow of food energy from the field to the dinner table shows that 16 kcal of plant energy derived from the sun are necessary to produce 1 kcal of food energy (Figure 5). The activities involved in making that one unit of food energy available for human consumption require an additional 7.1 units of fossil fuel energy. Thus a total of 23.1 units of energy, made up of 16 units of plant energy and 7.1 units of fossil fuel energy, are expended in return for one unit of food energy. The overall conversion efficiency is therefore only about 4.3 percent.

These analyses point out some of the dangers involved in calculating energy efficiencies of industrial processes. One must carefully describe the reference used.

Agriculture represents any effort to use soil, water, and land to produce food and fiber. Green plants absorb energy from the sun and convert it into forms of chemical energy suitable for human and animal consumption.

Table 3. Total energy consumption in million kilocalories (Mkcal) per person per year for food related activities in the United States for 1974 (FEA, 1975).

Category	Annual consumption	Percent of total
	Mkcal/person	%
FARM PRODUCTION	2.6	17.4
PROCESSING	4.3	28.9
DISTRIBUTION	1.2	8.0
PREPARATION AWAY FROM HOME	2.5	16.8
HOME PREPARATION	3.9	26.2
EQUIPMENT	0.4	2.7
TOTAL	14.9	100

Table 4. Total energy consumption in million kilocalories (Mkcal) per person per year for food related activities in Australia for 1974 (Anonymous, 1974).

Category	Annual consumption	Percent of total
	Mkcal/person	%
FARM PRODUCTION		
Fuel and Electricity	1.1	17.4
Fertilizers	0.4	6.3
Other	0.3	4.8
PROCESSING		
Transportation	0.2	3.2
In Plant	1.7	27.0
DISTRIBUTION		
Transportation	0.2	3.2
Trade	0.7	11.1
HOME PREPARATION		
Refrigeration	0.9	14.3
Cooling	0.8	12.7
TOTAL	6.3	100

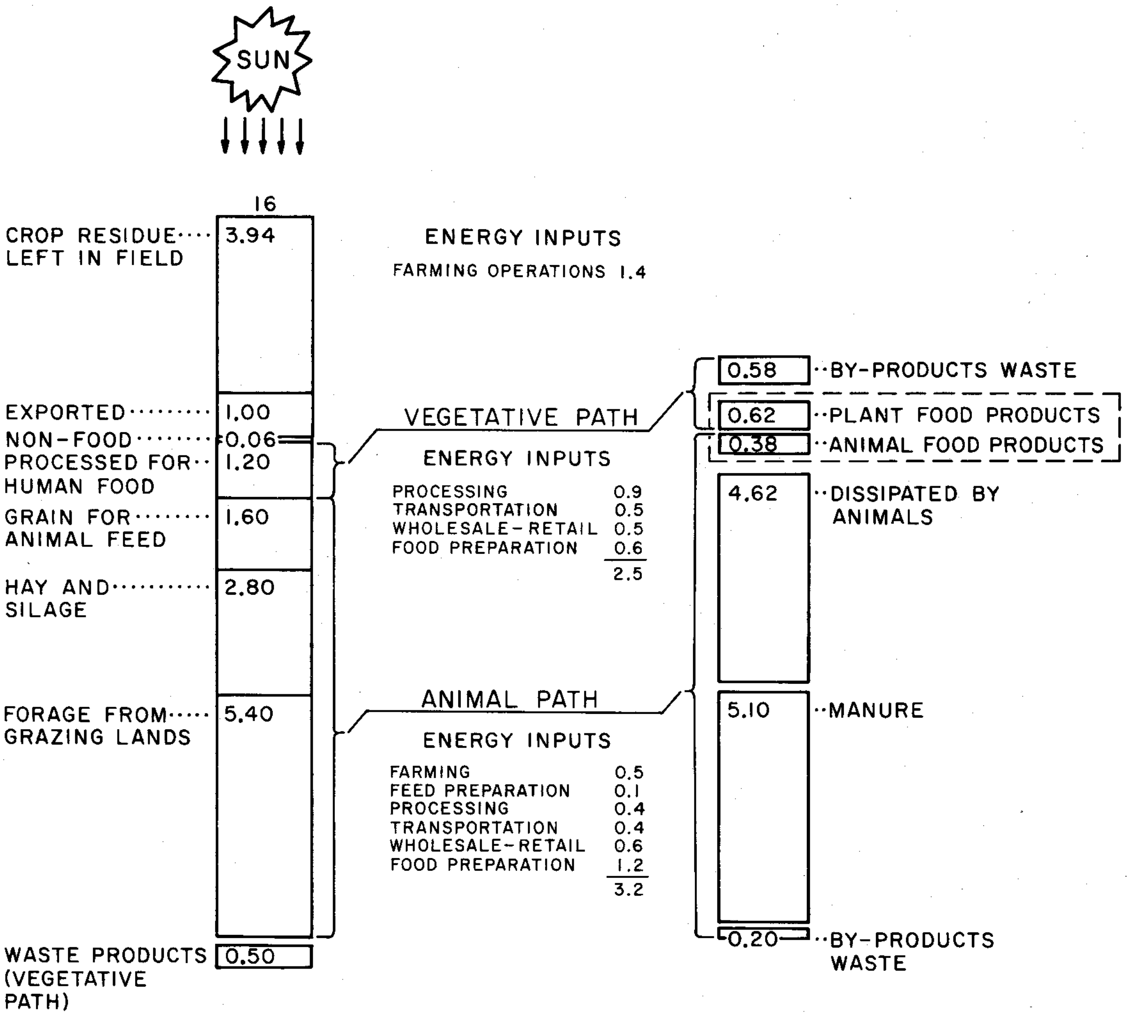

Figure 5. The flow of energy in food production (Nelson et al., 1975). Food energy produced and fossil fuel inputs are stated in kilocalories (kcal).

In the process of harvesting the sun's energy, other forms of energy are used. These can be in the form of human labor or fossil fuels such as oil and gas. In primitive societies nearly all energy used is in the form of human labor whereas in modern farming systems fossil fuels are used.

Recently, there have been numerous discussions about the "efficiency" of modern farming methods. The efficiency of energy use in farming is defined as the ratio of edible energy harvested divided by the energy used. Using this procedure, it can be shown that the efficiency ratio of energy use in the food production system consisting of hunting and food gathering is about 50 while that of modern agriculture is less than 1.0.

According to the estimate developed above, namely, that 8 kcal are required to produce 1 kcal of food energy, the Energy Ratio of modern agriculture is 0.12.

This calculation indeed results in a low efficiency of energy use. However, this result may not be used to demonstrate that the production of food by agriculture is inefficient.

First of all, of the 8.0 kcal needed to produce 1.0 kcal of food on the dinner table, only 18 percent or 1.4 kcal were used on the farm. Secondly, the 1 kcal of food energy actually consumed was obtained from 16 kcal of food energy initially grown in the field (Figure 5). Thus, the input of 1.4 kcal produced 16 kcal of food energy.

The Energy Ratio of U.S. agriculture is therefore 11.4 which is obtained by dividing 16 by 1.4. The growing of crops is a very energy efficient process. Indeed, farming is the only industrial process with a net energy gain.

Efficiency of Food Energy Use

Figure 5 shows what happens to the various forms of food energy grown in the U.S. It shows that 16 kcal of food energy grown in the field are required to produce 1 kcal of food energy on the table ready for consumption. This 1 kcal of food energy is made up of 0.38 kcal of animal products and 0.62 kcal of plant products.

Of the 16 kcal of plant energy produced, 3.94 are left behind in the field as a crop residue, 1.00 is exported to other countries where it will be available as food energy, 0.06 consist of non-food products such as cotton, flax, and tobacco, and 11.0 consisting of forage, grain, and other products are available for the domestic food chain.

How the 11 kcal are used is determined by consumer preferences, the need for a balanced diet which includes animal products, and the fact that many plant products can be digested by animals but not by people.

The food can follow the vegetative pathway and be consumed in the form of plant material such as fruits, breads, or cereals, or it can follow the animal pathway and be fed to animals to provide meat, dairy, and poultry products.

In the U.S., 1.2 of the 11 kcal available are processed for consumption as plant products and 9.8 are consumed by animals. Processing the 1.2 kcal along the vegetative path yields 0.62 of food and 0.58 of by-products and waste of which 0.50 are recycled in animal feed.

The animal pathway starts with a total of 10.3 kcal: 1.6 from grain, 2.8 from hay and silage, 5.4 from grazing land, and 0.50 from the waste products of the vegetative path. These 10.3 kcal produce 0.38 food, 5.1 manure, and 0.2 by-products and waste. The remaining 4.62 kcal are used by the animals to maintain their temperature and expend energy for grazing and other physical activities.

It has been said that food energy could be used with greater efficiency by making more plant products available for direct human consumption. This is not so. Of the 9.8 kcal used by the animals only the 1.6 kcal of grain could possibly be made available for human consumption. The materials collected from pastures and range lands cannot be digested by humans. The animals are needed to convert plant materials to a form suitable for human consumption.

It has also been suggested that the land from which the roughage is obtained could grow products, digestible by humans. Some of the land probably could be used in this manner, but only with a great cost of energy and capital. Traditionally, the poorer land, land with some limitation, has been reserved for forage production. Limitations include depth of soil, drainage condition, slope, rainfall, and erosion.

Efficiency of Solar Energy Use

One of the concepts being evaluated in this study is that the efficiency with which solar energy is captured by green plants can be increased by the recovery of the food energy remaining in the animal manure and the recovery of the nutrients in the manure.

Nelson et al. (1975) state that 16,000 kcal of solar energy are available for plant growth and produce the 16 kcal shown in Figure 5, indicating a photosynthetic conversion efficiency of 0.1 percent. From these, 1 kcal of food energy is obtained for a final conversion efficiency of 0.0063 percent.

Theoretically, higher photosynthetic efficiencies are possible. Of the radiation available at the earth's surface, only 43 percent can be used in the photosynthetic process, leaving 6,880 kcal. The efficiency of the photosynthetic process is 28.6 percent, leaving 1,968 kcal. But not all radiation is absorbed by plant leaves. About 20 percent is transmitted, leaving 1,574 kcal. One-third of the plant material accumulated is lost in respiration processes, leaving 1,050 kcal. Assuming that plants consist of about 60 percent shoots and 40 percent roots, 630 kcal should be available in the field for harvesting. The theoretical efficiency of obtaining food from solar energy is therefore 3.9 percent (630 kcal/16,000 kcal x 100). We have already noted that the actual efficiency is 0.1 percent.

The solar energy received by all cropland in the U.S. is estimated to be 4.13 x 10^{18} kcal per year. The area of cropland, pasture, and range is about 4 x 10^{8} ha, giving a radiation intensity of 1.03 x 10^{10} kcal/ha year. Assuming a growing season of 200 days, this radiation intensity corresponds to an average of 500 cal/cm^2 day during the growing season. This may be a reasonable estimate for the entire U.S., because it applies only to the months with the longest daylength and includes the regions with a low percentage of cloud cover.

The energy content of organic materials may range from 2.5 to 5.5 kcal/g of dry matter. For the photosynthetic efficiency of 0.1 percent indicated above, the radiation intensity of 1.03 x 10^{10} kcal/ha year corresponds to a yield of 1.03 x 10^{7} kcal/ha year. If we assume an energy content of 4.0 kcal/g this corresponds to 2.55 tons of dry matter per ha per year. If we assume the cropland to yield an average of 5 tons/ha year, the yield of pasture and range land would be 0.85 tons/ha year.

Assuming the theoretical efficiency of about 4.0 percent, the average yield should have been 102 tons/ha year. Yields of this magnitude have been measured. Why then are such yields not achieved consistently? Obviously, inputs other than sunlight are in short supply. These include, quality of soil, nutrient supply, water supply, plant species, and finally, land management.

Energy Requirements of Irrigation

A large portion of the land areas available for expansion of agricultural production lack water. This must be supplied by irrigation systems. Unfortunately, irrigation is a high energy user.

The high energy requirement of irrigation is shown in Table 5, listing the ratios of harvested food energy to cultural energy for several cropping systems producing corn grain. This ratio is 20 for the cultural system used in Ghana where the only input is human labor. Using more intensive farming systems by combining mechanical inputs with manual labor decreased the ratio to about 4.8 but increased yields substantially. Higher energy inputs increased yields so that the ratio remained constant during the early part of this century. A dramatic decrease occurred, however, where irrigation was required, as shown for California in 1972.

Table 5. Response of food energy yield from corn grain to increasing inputs of cultural energy (Heichel and Frink, 1975).

Cultural system	Energy input	Energy yield	Ratio
	..... Mkcal/ha yr		
Rainfed Agriculture			
Ghana, 1947	0.22	4.45	20.22
Iowa, 1915	3.95	18.77	4.75
Indiana, 1938	6.92	33.35	4.82
Illinois, 1969	12.84	56.07	4.37
Irrigated Agriculture			
California, 1972	30.38	66.94	2.20

It has been suggested that the arable land area can be increased by irrigation. About 12 percent of the world's cultivated land or 210 million hectares are now irrigated. Pimentel et al. (1975) estimate the energy cost of lifting the water needed to irrigate 1 ha of corn in the subtropics to be approximately 20 Mkcal. Assuming a lift of 90 meters, the authors estimate that 3,090 x 10^9 liters of fuel per year (sic.) would be required to increase the irrigated acreage of the world by 1.5 x 10^9 ha. This would exhaust known oil reserves (Jiler, 1972) in 20 years and potential reserves in 100 years (National Academy of Sciences, 1969). Although the authors' estimate of the fuel requirement is too high by a factor of 10 due to a mathematical error, the study points out that increasing the cultivated acreage by irrigation is not likely to succeed as the competition by all sectors of the economy for the remaining supply of fuel intensifies.

Water Availability

The availability of fresh water, measured in terms of quantity and place of occurrence, is one of the crucial problems in the evaluation of adequacy of resources for the continued development of mankind. This availability may, in the future, place constraints on the ultimate size of the population and on the standard of living that populations of any density will be able to enjoy. The need for water increases rapidly with higher living standards. Large quantities of water are needed in manufacturing processes of all kinds, power generation, home use, and food production. Producing one egg requires about 500 l of water, producing one loaf of bread requires 1,200 l, and putting one kg of beef on the table requires 30,000 l.

An estimate of the total amount of water in the world and its distribution (Table 6) shows that most of the water is in the oceans. The next largest quantity is locked in ice caps and glaciers. The sources of water available for farming are fresh water lakes, water in stream channels, and the sub-surface waters including the water in the unsaturated zone and the shallow and deep lying groundwater reservoirs. Most of present day agriculture is based on the use of water stored in the unsaturated, aerated zone of the soil.

Table 6. Water supplies of the earth. (After Leopold, 1974).

Location	Volume	Percent of total
	10^3 km^3	%
Surface Water		
Fresh water lakes	125.0	0.0089
Saline lakes and inland seas	104.1	0.0074
In stream channels	1.2	0.0008
Subsurface Water		
Soil water	66.7	0.0048
Shallow ground water <800 m	4,165.5	0.2984
Deep ground water >800 m	4,165.5	0.2984
Other Locations		
Ice caps and glaciers	29,158.6	2.0890
Atmosphere	12.9	0.0009
Oceans	1,357,956.0	97.2918

The Food and Agriculture Organization (FAO) of the United Nations (UN) estimates that 11 percent of the earth's land surface (1.5 billion hectares) is suitable for cultivation. As shown in Table 7, much of this land is not in use (Hendrix, 1969). Pastures, rangeland, and meadows used for raising livestock take up 22 percent of the land area. Forests cover 30 percent, while for 37 percent (4.8 billion hectares) no agricultural enterprise is economically feasible because the land is either too cold, too dry, or too steep. The land area used for raising field crops could be increased by cultivation but only with great difficulty. The energy limitations of the practice are evident.

The amount of water required for growing crops on irrigated land can be estimated by assuming that 100 cm of water would be required per year. This includes losses from storage, from canals, and the amount transpired by crops. Presently about 12 percent of the cultivated land is being irrigated or 210 million hectares. Thus on a worldwide basis, the total irrigation requirement is 1,800 km^3 of water per year. The annual requirement is therefore equivalent to 2.7 percent of the water available in the unsaturated zone or about 1.5 percent of the water stored in fresh water lakes.

Table 7. Percentage of potentially available land now cultivated (Hendrix, 1969).

Continent	Percent cultivated	Cultivated land per person
	%	m^2
Asia	83	2,833
Europe	88	3,642
South America	11	4,047
Africa	22	5,261
North America	51	9,308
USSR	64	9,713
Australia	2	11,736

These percentages appear to be small. But the fresh water lakes do not occur where the irrigation water is needed. Most sites suitable for irrigation reservoirs have already been put into use. Those remaining are located where the need for water is least. About one-third of the world's runoff passes through rivers in South America where only one-eighth of the land is located.

Most of the land where crops can be economically grown without supplemental irrigation are now in use as is indicated in Table 7. Much of the world's vacant land is in tropical South America and Africa. The vacancy there is not without reason. It occurs due to climatic limitations.

While large areas of vacant tropical lands are well watered, much of it is not. If it is assumed that an additional 1.5 billion hectares could be brought into production, the total irrigation requirement would be 15,000 km^3 per year. This quantity corresponds to an annual use of about 12 percent of all the water currently stored in fresh water lakes or 23 percent of the water stored in the soil. These numbers indicate that water shortage could indeed become a problem for expansion of agricultural production in the future.

Animal Waste Management

In the past, livestock were raised by many farmers who fed small numbers of animals. These dispersed operations kept manure concentrations relatively small. In most cases, the manure was applied to cropland on the farm where it was produced. Changing management practices now favor the concentration of large numbers of animals on a small land area as in outside feedlots and total confinement rearing units. Large quantities of waste accumulate which the local environment cannot assimilate without extensive damage to the quality of air and water unless appropriately managed. The manure currently produced by livestock in the U.S. exceeds 2 billion tons per year (Loehr, 1974). It contains nearly 300 million tons of dry matter, 10 million tons of nitrogen (N), 3 million tons of phosphorus (P), and 4 million tons of potassium (K). These N-P-K values are roughly equivalent to the U.S. consumption of chemical fertilizers in 1975 (Hargett, 1975).

Current manure management is expensive in terms of both equipment and labor. Highly mechanized manure management systems which give adequate consideration to environmental quality are essential if livestock production is to survive.

Public action programs to abate pollution have placed an urgency on research to develop methods for controlling concentrations of solids, nitrogen, and phosphorus which enter surface and ground water, and to control the odors arising from livestock operations. Animal wastes are also a potential source of pathogenic organisms which can be scattered into the environment and become a health hazard, particularly under the increasing demand for water-based recreational sites.

Swine Production Units

The animal waste selected for this study was swine manure, primarily because of ready access to the OSU Swine Research Center and the availability of land for the construction of the experimental facility.

In a recent review of swine waste production and pretreatment processes (Overcash and Humenik, 1976), the typical pig production facilities in the United States were found to fit into three major categories based upon waste management techniques used: (1) swine units with concrete slabs, (2) swine units with open pits over slatted floors, and (3) drylot or pasture operations. By far the largest number of the pig farms, namely 50 percent, use drylots for swine production, 30 percent use solid concrete floors, most only partially roofed, and 20 percent use slatted floor-pit units.

The need to reduce labor costs, in particular for waste cleaning, has reduced the desirability of solid concrete floors. Overcash and Humenik (1976) noted that, in terms of existing swine production units, there has been a slow but steady change toward total confinement buildings during the past 5 years. Confinement buildings offer enhanced feed conversion, high conception rates, and reduced mortality. However, high investment costs of confinement assure the continued use of the dirt lot as the preferred, low labor alternative to raising pigs in the foreseeable future.

The size of pig farms in terms of the number of animals marketed and the contribution of the farms in each category to the total number of pigs sold in 1969 are summarized in Table 8 (U.S. Dept. of Commerce, 1972). Farms selling over 1,000 pigs contributed 13 percent to the total number of swine sold; farms selling between 500 and 999 pigs accounted for 20 percent of the total market; farms selling 200 to 499 pigs accounted for 36 percent, and producers selling less than 200 animals contributed 31 percent to the total number of pigs sold in 1969. The majority of animals brought to market, namely 67 percent, were therefore contributed by farms which produced fewer than 500 pigs each.

Surveys conducted in 1971 and 1974 by the National Pork Producers Council (Overcash and Humenik, 1976) indicated a trend towards larger production units. The number of farms selling 500 pigs or less decreased during the 1971-74 period while the number producing more than 500 pigs increased. The largest increase was found in the group marketing 1,000 to 2,999 animals per year.

Table 8. The size of pig farms in terms of the number of animals marketed per year and the contribution made by farms in each category to the total number of pigs sold in 1969 (U.S. Dept. of Commerce, 1972).

Swine marketed per year per farm	Percent of swine marketed
	%
> 1,000	13
500 - 999	20
200 - 499	36
< 200	31

The survey further showed that an increasing number of confinements were high density, slatted floor-pit units. As far as management of the waste was concerned, by far the largest number of producers (90 percent) continued to return the manure to cropland and pastures.

Pig operations contribute about 23 percent to the total amount of animal waste produced in the U.S. or 11 x 10^6 tons of dry weight per year (U.S. Dept. of Commerce, 1969). In as much as dirt lots and pastures are still preferred by 50 percent of the pig operations, only a fraction of the total amount of swine manure produced appears to be collectible at present for the recovery of nutrients and energy by algae and anaerobic digestion.

A detailed analysis of the swine industry in North Carolina in 1974 (Overcash and Humenik, 1976) showed that 13 percent of the existing confinement units used solid concrete floors and raised 28 percent of the marketed pigs. Only 7 percent used slatted floors but raised 31 percent of the marketed pigs, while 80 percent used dirt lots and pastures and produced 41 percent of the total number of pigs marketed. Obviously, dirt lots and pastures are used most extensively by the smaller operations while slatted floor-pit units are common for the large, totally enclosed, and environmentally controlled units.

The trend in North Carolina and other pig producing states is towards these large confinement buildings. It is therefore reasonable to expect that most of the swine waste generated in the U.S. will become available for bioconversion processes which recover useful end products from the manure such as methane-rich fuel gas, single cell protein, and fish protein.

OBJECTIVES OF PROJECT

Figure 5 demonstrates that nearly 50 percent of the field grown plant energy consumed by livestock is wasted in the form of manure. The nutrients, minerals, and solids it contains could provide an adequate substrate for the production of single cell protein (SCP) by selected microorganisms. On the other hand, Figure 3 shows that the reject heat contained in the condenser cooling water of thermal power plants is of low grade (15 to 50 C), but ideally suited to maintain the elevated temperatures required for optimum rates of biological processes. These particular waste products of the livestock and the power generating industries, therefore, complement each other and could form the basic resources for an integrated production system.

Based on the premise that such systems would conserve water, nutrients, and energy, recycle nonrenewable resources, recover useful end products, and contribute to the improvement of environmental quality, an experimental facility was designed and built to evaluate the biological conversion of nutrients in swine manure to animal feed with a high protein content and to a methane-rich fuel gas. Waste heat was simulated to evaluate its potential for sustaining and increasing the efficiency of the conversion.

The facility included the following major components: a livestock confinement building, hydraulic manure transport, solid-liquid separation, anaerobic digestion of solids, culture basins supplied with the liquid portion of the swine waste for aerobic growth of microorganisms, and a centrifuge for harvesting the biomass.

The objectives of the studies were to establish:

(1) the extent of nutrient removal and conversion to protein and methane gas by photosynthetic and non-photosynthetic organisms,

(2) the energy requirements of the major conversion units, namely the anaerobic digester and the outdoor culture basins,

(3) the quality of the waste water that would be relased to the environment or returned to the system for re-use after the removal of the biomass,

(4) the biological stability of the conversion units,

(5) the usefulness of the recovered biomass as a protein supplement in feed rations,

(6) the economics of the system on the basis of its energy requirements, biological reliability of the anaerobic digester and the outdoor culture basins, and yields of these conversion units, and

(7) the criteria for full-scale design and operation.