Biogas processes for sustainable development

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Acknowledgment

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The most important of all are the researchers and technologists who are involved in the Biogas development. They are the key people to achieve the sustainable development so many people are referring to. Their work and research which is quoted in this review presents only a small portion of the important progress in Biogas technology and all my thanks are due to them.

In addition I am grateful to my colleagues in MIGAL, especially to George Ney who helped me so much in bringing this review to its final form.

Chapter one: Preface and objectives of the review

Sustainable development

There is an increased recognition, in both developing and industrial countries, of the need for technical and economic efficiency in the allocation and exploitation of resources. Systems for the recovery and utilization of household and community wastes are gaining a more prominent place in the world community. Today, a new environmental agenda is emerging, which is now forcing itself on the attention of policy-makers and the public at large. Its concerns are both practical and urgent: they address the survival of human, animal and plant populations over vast sections of our globe.

Today's issues arise from the spread of deserts, the loss of forests, the erosion of soils, the growth of human populations and industrialized animal husbandry, the destruction of ecological balances, and the accumulation of wastes. As a result, the politics needed to meet present and future challenges require a new vision and new diplomacy, new leadership and new policies. In a world that is daily more complex and economically interdependent, the economic and security interests of the Developing Countries must be understood in a broader, global context.

These acute, relatively new problems of the world stem from either poverty and excessive population growth, in the Developing Countries, or from the careless and excessive use of natural resources in the Developed Countries; with more cumulative impact on the poor countries than on the rich. While many of these problems have been recognized for some time, they demand a new policy agenda for the world. The emergence of such a new approach has been accompanied by the growing realization that the goals of environmental conservation and economic growth in both developing and industrial countries are more complementary than often depicted. A.W. Clausen, President of the World Bank, has stressed these relationships: "There is increasing awareness that environmental precautions are essential for continued economic development over the long run. Conservation, in its broad sense, is not a luxury for people rich enough to vacation in scenic parks. Rather, the goal of economic growth itself dictates a serious and abiding concern for resource management".

Necessary goals are to achieve economic and environmental benefits through sustainable projects for resource recovery and utilization, and programs for Developing Countries. The use of anaerobic digestion in an integrated resource recovery system in Developing Countries is important to solve both ecological and economic problems.

Sustainability in waste management systems depends upon the interrelationship of policy, technique and

economy. This interrelationship is particularly important in integrated resource recovery systems. This review aims to provide governments, development agencies, consultants and others with information necessary for the development and implementation of policy on waste management. It summarizes the latest developments in anaerobic digestion applicable to Developing Countries, as reported in English-language publications up to the year 1990. The review is prepared in an attempt to answer the questions of officials in Developing Countries about anaerobic digestion facilities throughout the world to provide health and economic benefits by digesting (fermenting) animal wastes, residues from harvesting, night soil and, in a number of cases, also from septage and sludges. The review summarizes the main issues of anaerobic digestion and its fundamentals in both the microbiological and practical aspects, discusses the various products of the process and their uses, alone or in integrated resource recovery systems, in different parts of the world, provides a brief review of the economic aspect of both household and commercial plants, and gives some information on biogas programs in several Developing Countries, their advantages and drawbacks. The review also includes some technological information and a bibliography of additional sources of information, as well as a list of companies and groups in different parts of the world involved in biogas technology.

It may be asked why a new review is called for.

1. When oil prices began dropping in 1986, oil users everywhere sighed with relief, but the energy crisis did not end, in fact. More than half the world's people cook and heat with firewood, dung and field residues. For most of these people, cheap oil is little cause for celebration, while bioenergy development, on the other hand, is a realistic proposition for a better social and economic life. The new developments and technologies in this field must be distributed and incorporated into the existing infrastructure of Developing Countries.

2. Today, anaerobic digestion is widely accepted as a sound technology for many waste treatment applications, and novel reactor designs are being applied on a commercial scale. In spite of this acceptance, advances are still being made, and technological developments are concentrating on applications in Developing Countries.

3. New and already developed approaches and processes for upgrading the quality and use of the effluent from anaerobic digestion are the reason for more economical uses of bioenergy processes.

4. Effective biodegradation of organic wastes into methane requires the coordinated metabolic activities of different microbial populations. Recent results of physiological and biochemical experiments are presented, in order to explain the fundamentals of mixed culture metabolism, which influence the rate of organic degradation.

5. The enormous development of computer technology and use makes simulation and model projections of the anaerobic digestion processes possible, on the one hand, and facilitates the use of developed control systems in the processes, on the other.

6. Last, but not least, the ecological aspect: the concern for the environment has come to the consciousness of the world, and we now understand better that our environmental heritage must be protected, for the sake of the quality of our lives and those of our children. This attitude is now beginning to govern our behaviour in waste management,

and is encouraged increasingly by governments in both Developed and Developing Countries.

This review is therefore intended to up-date students, practitioners and consultants concerned with Biogas technologies, and to contribute to bringing biogas systems to a more advanced stage, and thereby to achieve a palpable impact in Developing Countries.

Sustainable development

Probably the most serious source of conservation problems faced by Developing Countries is the backwardness of rural development. In the struggle for food and fuel, large areas of vegetation, trees and shrubs, are felled and stripped for firewood, cultivation and fodder. The consequence is the impairment of ecological processes in these countries, and the permanent destruction of normally renewable resources. There is an urgent need for rural development that combines short term measures for survival with long-term measures to safeguard the resource base and improve the quality of life, while ensuring the future. Unfortunately, many rural communities are so poor that they lack the economic flexibility that would enable them to defer the consumption of resources in need of restoration. Conservation measures are needed that will, at the least, maintain the standard of living of these communities, or improve it, while taking into account their own knowledge of the ecosystem, and finding effective ways to ensure that these resources are used sustainably.

According to the World Conservation Strategy towards sustainable development (as set out by IUCN, UNEP, WWF, FAO and UNESCO), which recognizes the need for international action to implement it, and to stimulate and support national action, an integrated approach to many of the problems involved is necessary. Cooperation between nations and organizations can facilitate the deployment of the limited means available, and thereby enhance the prospects for conservation and for sustainable development. Joint international action can do a great deal towards restoring the environment, tackling environmentally induced poverty, and enabling countries to make the best use of their resources, provided that the projects so supported are environmentally sound and assessed with due consideration for the local ecology. The first objective of the World Conservation Strategy is to maintain essential ecological processes, such as soil regeneration and protection, recycling of nutrients, and the cleansing of water, on which human survival depend. Part of this objective can be achieved, as a matter of urgency, by procedures for the rational use of organic matter, in Developing Countries, to help rural communities conserve their basic living resources, the essential springboard for development of energy and land.

One of these procedures is the production of biogas from organic agricultural wastes. These materials are destructible without proper conservation methods, but otherwise can yield a great sustainable benefit, at farm level. In order to achieve the World Conservation Strategy in this particular field, an increase in the number of trained personnel, and much wider awareness, are needed, as well as research-oriented

management with the necessary basic information. Conservation and sustainable development, in rural communities whose only fuel is wood, dung and crop wastes, is all that stands between them and destruction. Biogas production combines the short-term economic needs of such communities with conservation and the end of ecological degradation.

Chapter two: Introduction and overview

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Anaerobic treatment is the use of biological processes, in the absence of oxygen, for the breakdown of organic matter and the stabilization of these materials, by conversion to methane and carbon dioxide gases and a nearly stable residue. As early as the 18th Century the anaerobic process of decomposing organic matter was known, and in the middle of the 19th Century, it became clear that anaerobic bacteria are involved in the decomposition process. But it is only a century since anaerobic digestion was reported to be a useful method for the treatment of sewage and offensive material. Since that time, the applications of anaerobic digestion have grown steadily, in both its microbiological and chemical aspects. The environmental aspect and the need for renewable energy are receiving interest and considerable financial support in both Developed and Developing Countries, expanding research and application work in these directions, and many systems using anaerobic digestion have been erected in many countries.

Anaerobic digestion provides some exciting possibilities and solutions to such global concerns as alternative energy production, handling human, animal, municipal and industrial wastes safely, controlling environmental pollution, and expanding food supplies.

Most technical data available on biogas plants relate primarily to two digester designs, the floating cover and fixed dome models. Promising new techniques such as bag, dry fermentation, plug flow, filter, and anaerobic baffled reactors should be explored to establish a firmer technical base on which to make decisions regarding the viability of biogas technology. Along with this increase in interest, several newer processes have developed, that offer promise for more economical treatment, and for stabilizing other than sewage materials - agricultural and industrial wastes, solid, organic municipal residues, etc. - and generating not only an alternative energy source, but also materials that are useful as fodder substitutes and substrates for the mushroom and greenhouse industries, in addition to their traditional use as organic fertilizers. Other benefits of anaerobic digestion include reduction of odours, reduction or elimination of pathogenic bacteria (depending upon the temperature of the treatment) and the use of the environmentally acceptable slurry.

The technology of anaerobic digestion has not yet realized its full potential for energy production. In most industrialized countries, biogas programs (except for sewage treatments) are often hindered by operational difficulties, high costs of plants and as yet low energy prices. In most Developing Countries, expansion of biogas programs have been hindered because of the need for better economic initiatives, organized supervision and initial financial help, while in other Developing Countries, on the other hand, slow development has been observed, and a lack of urgency, because of readily available and inexpensive non-commercial fuels, such as firewood.

Biogas technology is also potentially useful in the recycling of nutrients back to the soil. Burning non-commercial fuel sources, such as dung and agricultural residues, in countries where they are used as fuel instead of as fertilizer, leads to a severe ecological imbalance, since the nutrients, nitrogen, phosphorus, potassium and micro-nutrients, are essentially lost from the ecosystem. Biogas production from organic materials not only produces energy, but preserves the nutrients, which can, in some cases, be recycled back to the land in the form of a slurry. The organic digested material also acts as a soil conditioner by contributing humus. Fertilizing and conditioning soil can be achieved by simply using the raw manure directly back to the land without fermenting it, but anaerobic digestion produces a better material. Chinese workers report that digested biomass increases agricultural productivity by as much as 30% over farmyard manure, on an equivalent basis (van Buren 1979). This is due in part to the biochemical processes occurring during digestion, which cause the nitrogen in the digested slurry to be more accessible for plant utilization, and to the fact that less nitrogen is lost during digestion than in storage or comporting. The stability of the digested slurry and its low BOD and COD are also of great importance. This aspect of biogas technology may, in fact, be more important than the gas produced (Gosling 1980; Marchaim 1983).

In the area of public health and pollution control, biogas technology can solve another major problem: that of the disposal of sanitation wastes. Digestion of these wastes can reduce the parasitic and pathogenic bacterial counts by over 90% (Feacham et al. 1983; McGarry and Stainforth 1978; van Buren 1979; Klinger and Marchaim 1987), breaking the vicious circle of reinfection via drinking water, which in many rural areas is untreated. Industrial waste treatment, using anaerobic digestion, is also possible.

Many planners and engineers have expressed an interest in obtaining information on anaerobic digestion and biogas technology. Application to FAO in Rome of the fundamentals of design and operation of digesters to enhance their technical and economic viability, were the main reason for this review. An additional review, which will describe more technical aspects, will be published, in order to explain the complexity of this interdisciplinary technology, which requires a broad overview of the whole program for optimal selection of size and style of the digestion system.

The present review attempts to present only very basic information on the engineering aspect, while giving some more detailed description of the biochemistry and microbiology, and emphasizing the economic and socio-cultural aspects of biogas programs and the uses of the products of the anaerobic digestion process, especially as they may be applied in Developing Countries. References cited can provide studies of given areas of interest, in greater depth. The chapter on biogas products and their uses gives an idea of the potential applications of biogas and digested slurry technologies.

This review is also intended to assist engineers and government officials/funding agencies to meet present and future challenges, and make decisions on the promotion of anaerobic digestion as an alternative source of energy, for soil conservation and enrichment, as fodder for fish and animals, for pollution reduction and other ecological benefits, such as pathogen reduction in human and animal wastes.

Current research, experimental and functional programs throughout the world, are rapidly adding to our knowledge of anaerobic digestion, and should provide increasingly efficient and useful designs to improve the quality of life everywhere. The AD meetings - The International Symposiums on Anaerobic Digestion that are held every 2 - 3 years - are a very good occasion to get up-to-date information on latest developments. The Proceedings published after each of these meetings can be very valuable to researchers, officials and economic analysts.

In order to draw conclusions about the feasibility of the anaerobic digestion process, it can be examined in one of two ways: a strictly financial approach, involving analysis of monetary benefits such as sale or re-use of products (methane, carbon dioxide and slurry, with all its applications) and the costs of constructing and maintaining facilities; or as a social assessment of input and output, including such intangibles as improvements in public health, reduced deforestation and reduced reliance on imported fossil fuels, in a social cost benefit analysis. There is no agreed methodology for quantifying these social benefits, so rigorous economic comparisons between biogas and other renewable, as well as conventional, energy sources are difficult, and must be done according to local conditions.

In assessing the economic viability of biogas programs, it is useful to distinguish between four main areas of application:

> 1) individual household units;
> 2) community plants;
> 3) large scale commercial animal rearing operations, and
> 4) municipal/industrial projects.

In each of these cases, the economic feasibility of individual facilities depends largely on whether output in the forms of gas (for cooking, lighting, electricity and power) and slurry (for use as fertilizer/soil conditioner, fishpond or animal feed) can substitute for the costly fuels, fertilizers or feeds which were previously purchased. For example, a plant has a good chance of being economically viable when the farmers or communities previously paid substantial percentages of their incomes for fuels (e.g. gas, kerosene, coal) and/or fertilizers (e.g., nitrates or urea) or peat-moss as soil conditioner for greenhouses. The economics may also be attractive in farming and industry, where there is considerable cost involved in disposing of manure or effluent. In these cases, the output can be sold or used to reduce energy costs, repaying the original capital investment. In those cases when the community is charged for treatment of the wastes, or if fines are imposed, the process is of great financial importance. If output/products do not generate income or reduce cash outflow, then the economic viability of a biogas plant decreases; for example, when cooking fuels such as wood or dung can be collected at no cost, or where the cost of commercial fuel is so low that the market for biogas is limited.

If the broader criteria are used to evaluate anaerobic digestion, especially in countries where officials and natural strategy people are more aware of ecology, where the effects of global warming over the long term (the Greenhouse Effect) is considered, then determination of viability requires knowledge of real resource or opportunity costs of input and output. When such output as improved public health,

greater rural self-sufficiency, reduced deforestation and reduced dependence on imported fossil fuels can be incorporated, the global economic analysis usually results in more positive conclusions than a purely monetary analysis.

Technical, social and economic factors, government support, institutional arrangements, and the general level of commercial activity in the construction of biogas plants and related equipment are highly interrelated. All influence the development of biogas programs. Focusing attention on any one aspect will not bring about successful results. A large variation exists in the number of digesters installed in Developing Countries throughout the world, depending on the extent of government interest and support. China, India and South Korea, have installed large numbers of units, ranging from some seven million plants in China to approximately 30,000 in South Korea. Other Developing Countries have fewer than 1,000 - usually less than 200. The relative poverty of most rural and urban people in Developing Countries, and their concomitant lack of capital, are especially powerful economic considerations. On the one hand, program growth will be slow if facilities require a relatively large number of people to cooperate and alter their behaviours simultaneously, but on the other hand this can improve tremendously the economics of the plant and the benefits to the community.

Some of the large scale projects erected in rural area proved to be economic viable much more than the household small scale systems, which lack maintenance and efficient exploitation of the plant's products. Some very interesting activities in communal biogas operation have already been working for a number of years in Italy (De Poli 1990). Commercial and private sector interest in anaerobic digestion is steadily increasing, in conjunction with government tax policies, subsidies which alter prices of competing fossil fuels and fertilizers, and pollution control laws, all of which affect the growth of biogas programs. Institutional program structure and government policies are the primary administrative and driving forces behind biogas implementation. In many developing countries the infrastructure to disseminate information on biogas to technical personnel, policy makers and potential users does not exist. Both qualitative and quantitative assessments of ongoing activities are needed to improve technology and adapt its use to each specific country. Generally, program coordination does not exist, except in China, between R & D projects and implementing agencies. Biogas programs which have expanded rapidly have had strong government support, including subsidized capital and tax incentives.

To summarize, biogas technology is receiving increased attention from officials in Developing Countries, due to its potential to bring an economically viable solution to the following problems:

   a. Dependence on imported sources of energy;
   b. Deforestation, which leads to soil erosion and therefore to a drop in agricultural productivity;
   c. Providing inexpensive fertilizers to increase food production;
   d. The disposal of sanitary wastes, which cause severe public health problems;
   e. The disposal of industrial wastes, which cause water pollution.

With the growing significance of this process, it is appropriate to mention some the historical

developments which have occurred during the last 100 years of anaerobic digestion. In many cases, this may help to clarify the state-of-the-art at the end of the 20th Century.

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Chapter three: Short historical background on anaerobic digestion

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Historical developments of anaerobic digestion technology

The appearance of flickering lights emerging from below the surface of swamps was noted by Plinius (van Brakel 1980) and Van Helmont recorded the emanation of an inflammable gas from decaying organic matter in the 17th Century. Volta is generally recognized as putting methane digestion on a scientific footing. He concluded as early as 1776 that the amount of gas that evolves is a function of the amount of decaying vegetation in the sediments from which the gas emerges, and that in certain proportions, the gas obtained forms an explosive mixture with air.

In 1804 - 1810 Dalton, Henry and Davy established the chemical composition of methane, confirmed that coal gas was very similar to Volta's marsh gas and showed that methane was produced from decomposing cattle manure. France is credited with having made one of the first significant contributions towards the anaerobic treatment of the solids suspended in waste water. In 1884 Gayon, a student of Pasteur, fermented manure at 35°C, obtaining 100 liters of methane per m of manure. It was concluded that fermentation could be a source of gas for heating and lighting. It was not until towards the-end of the 19th Century that methanogenesis was found to be connected to microbial activity. In 1868, Bechamp named the "organism" responsible for methane production from ethanol. This organism was apparently a mixed population, since Bechamp was able to show that, depending on the substrate, different fermentation products were formed. In 1876, Herter reported that acetate in sewage sludge was converted stoichiometrically to equal amounts of methane and carbon dioxide (Zehnder 1978, 1982).

As early as 1896, gas from sewage was used for lighting streets in Exeter, England, while gas from human wastes in the Matinga Leper Asylum in Bombay, India, was used to provide lighting in 1897. Then, in 1904, Travis put into operation a new, two-stage process, in which the suspended material was separated from the wastewater, and allowed to pass into a separate "hydrolyzing" chamber. In 1906, Sohngen was able to enrich two distinct acetate utilizing bacteria, and he found that formate and hydrogen, plus carbon dioxide, could act as precursors for methane.

On the applied side, Buswell began studies of anaerobic digestion in the late 1920s and explained such issues as the fate of nitrogen in anaerobic digestion, the stoichiometry of reaction, the production of energy from farm wastes and the use of the process for industrial wastes (Buswell and Heave 1930;

Buswell and Hatfield 1936).

Barker's studies contributed significantly to our knowledge of methane bacteria, and his enriched cultures enabled him to perform basic biochemical studies (Barker 1956). Schnellen (1947) isolate two methane bacteria: Methanosarcina barker) and Methanobacterium formicicum which are still studied.

Heating digestion tanks made practical use of the methane produced by the anaerobic process. It is of interest to note that methane gas was collected in Germany in 1914-1923 and used to generate power for biological treatment of plants, as well as for the cooling water from the motors being used to heat the digestion tanks.

Numerous additional studies led to a better understanding of the importance of seeding and pH control in the operation of anaerobic digestion systems. Much of this work is still relevant today, and those who are developing biogas as an energy source would gain much from review of this earlier work.

Present interest in anaerobic digestion

There is an increased recognition, in both developing and industrial countries, of the need for technical and economical efficiency in the allocation and exploitation of resources. Systems for the recovery and utilization of household and community wastes are gaining a more prominent place in the world community. During the last years, anaerobic fermentation has developed from a comparatively simple technique of biomass conversion, with the main purpose of energy production, into a multi-functional system:

> a) treatment of organic wastes and wastewaters in a broad range of organic loads and substrate concentrations;
> b) energy production and utilization;
> c) improvement of sanitation; reduction of odors;
> d) production of high quality fertilizer.

R & D has shifted from basic studies on anaerobic fermentation of quasi-homogeneous substrates, with contents of organic solids in the range of about 5 - 10%, to the digestion of more complex materials that need modified digester designs. The main fields of R & D activities are:

> a) fermentation at high organic loadings;
> b) high rate digestion of diluted waste waters of agro-industries including substrate separation during fermentation; immobilization of the microorganisms;
> c) fermentation and re-use of specific materials in integrative farming systems;
> d) biogas purification;
> e) simple but effective digested design/construction of standardized fermenters;

f) domestic waste water treatment.

Anaerobic digestion with high organic load can be performed when the concentration of methanogenic bacteria is kept at a high level. Pilot experiments, with mixtures of slaughterhouse waste water and cattle manure, succeeded in reducing retention times from about 20 to 8 - 10 days, by a specific mixing technique, which allowed the mixture from time to time to separate. By this method, the liquid phase is enriched with dissolved organic matter, which is brought into contact with solid material, containing a relatively high concentrations of active bacteria.

Dissolved organic compounds can normally be degraded much faster than solid materials in suspension. If the retention times for dissolved and suspended components can be adjusted separately, the overall process can be performed at higher rates. Similar techniques are under investigation or implementation into large scale application in most of the countries which perform biogas R & D activities and biogas promotion programs. For example, in the Netherlands intense work is done to reduce the concentration of organic matter in the digested materials, and to reduce the volume of liquid effluents of agricultural activities. In that country, with its intensive animal production, problems of soil and groundwater pollution become more and more severe - a situation similar to other countries with intensive agricultural production.

A two-step system is being developed and tested for agricultural solid wastes (greenhouse waste, organic fractions of municipal refuse, cannery waste, grass clippings). The first step is a batch type hydrolytic/acidic unit, in which percolation water is circulated. The percolation water is anaerobically treated in the second step, and recycled to the percolation unit. The retention time of the waste in the first step depends on the digestibility of the raw material, and can take several months.

Another system is being tested for treatment of the organic fraction of municipal refuse. After mixing with recirculated water and subsequent maceration, the waste is pumped into the first step reactor. Here the conditions (temperature 37C, hydraulic retention time 12 - 24 h) are such that a very efficient microbial population develops, that degrades cellulose. This population, in which ciliated play an important role, resembles the population in the paunch of ruminants. After passing the first step reactor, the mixture is mechanically drained, the liquid fraction is anaerobically treated (e.g. in an UASB-type reactor) and recirculated to the mixture tank. The solid fraction is partly forced back into the first step reactor, the remainder being discharged. To cope with water shortage and water pollution in the medium/long-term, a 6 year R & D project for water re-use and energy recovery by biogas production has been implemented in Japan since 1985, under the sponsorship of the Ministry of International Trade and Industry ("Aqua Renaissance 90"). The object of this project is to establish the technology to ensure a low cost treatment of industrial waste water, sewage etc. to enable re-use of treated water by utilizing a big-reactor - working at high concentrations - coupled with membrane-separation techniques, and which allows the efficient production of methane and other useful resources as well.

The main areas of this project are:

a) Microorganisms and big-reactors (fixed beds, fluidized beds, two phase binary tank, UASB-processes);

b) Membrane techniques: materials (organic polymers and ceramics) and modules;

c) Control and sensor system: a direct measurement of activity of microorganisms to control and optimize methane production;

d) Total water treatment system: a technology to integrate all the above methods.

By studying the structure of the hierarchy that promotes biogas digestion system in some of the Developing Countries, which is the key to the efficient and wide distribution of biogas plants in those countries, officials can profit for their own country. This review summarizes the latest developments in anaerobic digestion applicable to Developing Countries, as reported in English language publications up to the year 1990, and the lessons from newly developed systems can be applied in other countries. Sharing the new ideas and their economic benefits, especially for the uses of digested slurry, can be beneficial to most Developing Countries.

Although the problems of stratospheric ozone depletion, (the Greenhouse Effect) and climatic changes, resulting from deforestation and wrong treatment of the environment, have not yet reached the same level of public recognition as toxic waste treatment, more and more people are becoming aware of and concerned about them. These problems are dramatic new reminders that we live on a valuable planet, and we have to think and act in consort and deal in a global, integrated, way with all our organic wastes as well as the woods and the forests.

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Chapter four: Microbiology biochemistry and physiology

The literature on anaerobic digestion is replete with information on the microbiology and biochemistry, environmental factors, biodegradability, kinetics, and health aspects of the anaerobic digestion process. A knowledge of these fundamentals is useful in the design and operation of efficient digesters, and in understanding how upset conditions can occur and how to alleviate them. Below is a general discussion of key concerns.

Microbiology and biochemistry

The degradation of organic matter to produce methane relies on the complex interaction of several different groups of bacteria. Stable digester operation requires that these bacterial groups be in dynamic and harmonious equilibrium. Changes in environmental conditions can affect this equilibrium and result in the buildup of intermediates which may inhibit the overall process. It is of utmost importance to understand the basic microbiological and biochemical pathways, in order to master the biogas digestion system; and therefore the basic information on anaerobic digestion is summarized hereafter.

Omelianski's classic studies on methane fermentation of cellulose were reported in the 1890s. He

isolated organisms that produced hydrogen, acetic, and butyric acids. He also reported the formation of methane from hydrogen and carbon dioxide: $4H_2 + CO_2 = CH_4 + 2H_2O$.

Later, Soehngen (1910) confirmed Omelianski's findings. Perhaps of more significance today, Soehngen intimated that fermentations of complex materials proceeded through oxidation reduction reactions to form hydrogen, carbon dioxide and acetic acid. While he demonstrated that hydrogen reacted with carbon dioxide to form methane, he also assumed that the acetic acid produced was simply decarboxylated to form methane and carbon dioxide. This assumption was to remain highly controversial for decades, but is now known to be essentially correct. Today the importance of maintaining a correct balance between the two phases is well recognized, and the two-phase concept is widely used in the control of the anaerobic process.

The work of Buswell and his colleagues in the Thirties (1930a,b; 1938) led to better understanding of process control, and gave insights into the mass balance between substrate composition and methane production. Of significance was the demonstration that the following stoichiometric equation was applicable for methane fermentation of substrates in general (Kenealy et al. 1981):

$$C_nH_aO_b + (n-a/4-b/2)H_2O = (n/2-a/8+b/4)CO_2 + (n/2+a/8-b/4)CH_4$$
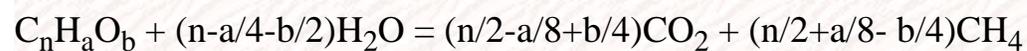
The "carbon dioxide reduction theory", developed in the 1930s, estimated that acetate oxidation should result in removal of hydrogen atoms, and methane would result as a consequence of a combination with carbon dioxide which served as a terminal electron acceptor. Buswell and Sollo (1948), using newly available ^{14}C tracers proved that methane formation from acetate did not occur through CO_2 reduction, and subsequently Stadtman and Barker (1949) and Pine and Barker (1956) conducted experiments that added further verification to the decarboxylation hypothesis. Using radiotracers, Jeris and McCarty (1965) showed that about 70% of the methane that resulted from the overall fermentation of most organic compounds and mixtures of compounds came from acetate, which was formed as an intermediate. The proportion resulting from acetate was predictable from normal biochemical pathways of oxidation.

One significant puzzle remained in this picture, and that was why it was so difficult to isolate the methanogenic bacteria. Barker's extensive studies (1940) led to the reported isolation of an organism, Methanobacterium omelianski, which oxidized ethanol to acetate and methane. Later, Hungate (1950) developed techniques which resulted in the isolation of several bacteria capable of converting CO_2 and H_2 to CH_4 However, the isolation of bacteria capable of converting propionate, butyrate, or higher fatty acid salts to acetate and methane could not then be accomplished. Hypotheses began to develop that a single organism may not be involved in these transformations, and experiments were devised to help prove or disprove the multiple-organism theory.

A major break occurred in 1967 when Bryant et al. (1967) reported that the original M. omelianski

culture contained two bacterial species, not one. By isolating each species, it was clearly demonstrated that one converted ethanol to acetate and hydrogen, and the other converted carbon dioxide and the released hydrogen to methane. Thus, it was recognized that the complete oxidation of a simple compound such as ethanol to carbon dioxide and methane would require contributions, combination and coordinated metabolism of different kinds of carbon catabolizing, anaerobic bacteria species. At least four different trophic types of bacteria have been isolated from anaerobic digesters, and these bacteria can be recognized on the basis of substrates fermented and metabolic end products formed (Imhoff 1938). The four metabolic groups which function in anaerobic digestion include (a) the hydrolytic and fermenting bacteria, which convert a variety of complex organic molecules (i.e., polysacharides, lipid and proteins) into a broad spectrum of end products (i.e., acetic acid, H_2/CO_2, monocarbon compounds,

organic fatty acids larger than acetic, and neutral compounds larger than methanol); (b) the hydrogen-producing acetogenic bacteria, which include both obligate and facultative species that can convert the products of the first group - the organic acids larger than acetic acid (e.g. butyrate, propionate) and neutral compounds larger than methanol (e.g. ethanol, propanol) to hydrogen and acetate; (c) the homoacetogenic bacteria which can convert very wide spectrum of multior monocarbon compounds to acetic acid; (d) the methanogenic bacteria which convert H_2/CO_2, monocarbon compounds (i.e.

methanol, CO, methylamine) and acetate into methane, or can form methane from decarboxylation of acetate (Fig. 4.1)

[Fig 4.1: The stages of methane fermentation.](#)

While the overall conversion of complex substrates into methane requires the synergistic action of all groups, the syntrophic association of the hydrogen producers of the second group and the hydrogen oxidizers in the third group is particularly unusual. In order for energy to be available to the organism oxidizing propionic acid to acetic acid and hydrogen, the partial pressure of H_2 may not exceed

approximately 10^{-6} atmospheres (Thauer et al. 1977). At this low pressure, the energy available to the hydrogen-oxidizing bacteria is reduced considerably from what it would be at partial pressures near 1 atmosphere. This results in much lower bacterial yields per mole of hydrogen gas oxidized, as confirmed by the low overall growth yields measured by Speece (1964) and Lawrence (1969) for complete methane fermentation of propionate and other fatty acids, as well as by thermodynamic predictions (McCarty 1971a).

These findings emphasize the important symbiotic relationships that must exist in anaerobic treatment. However, their practical consequences have yet to be demonstrated.

Over the last thirty years, there have been many process developments both for the enhancement of anaerobic treatment of municipal sludges and for the treatment of industrial wastewaters. During the 1950s two developments were of particular significance: one was the use of mixing in digesters and the other was the development of the anaerobic contact process.

Prior to 1950, most separate digesters treating municipal wastewater sludges did not employ mechanical

mixing. This resulted in the separation of solids from the liquid, forming a floating scum layer at the top of the digester and a thickened sludge at the bottom of the tank (Fig. 4.2). Scum layers often became several feet thick and reduced the overall capacity of the digester. It was found that mixing not only removed the scum layer, but enhanced the rate of digestion by bringing bacteria and wastes more closely together. Most modern digesters employ some form of mixing.

Figure 4.2: Conventional and high-rate digesters (From McCarty 1982)

Figure 4.3: Suspended-growth digesters designed to maintain high bacterial population allowing reduction in hydraulic detention time (From McCarty 1982)

Stander (1950) recognized the value of maintaining a large population of bacteria in the methane-producing reactor. By separating the bacteria from the effluent stream and keeping them in the reactor, he was able to reduce the retention time for efficient treatment down to as low as 2 days in the laboratory scale treatment of several different wastewaters from the fermentation industry. He later demonstrated the validity of these concepts in full-scale treatment of winery wastewaters in an anaerobic "clarigester" reactor, employing a settling tank for the return of bacterial solids and located over the digester (Fig. 4.3). Independently, a similar concept was used in the anaerobic contact process (Fig. 4.3) developed by Schroepfer et al. (1955) for the treatment of packinghouse wastes. These wastes were more dilute than municipal sludges, and a method was desired to reduce the retention time required for treatment. Borrowing from the aerobic activated- sludge process, they added a settling tank to the reactor effluent to collect and recycle bacteria. In this way retention times were reduced from the conventional 20 days, or longer, to less than 1 day.

The efficiency of treatment in a conventional digester operated at a given temperature, is related more to the retention time than to the rate of organic loading per unit of tank volume. This finding is consistent with the general theory of the relationship between organism or solids retention time and efficiency of waste treatment (Garret and Sawyer 1952). It was shown (McCarty 1966) that wash-out of the acetate-utilizing methane bacteria and the consortiums using propionate and butyrate occurred with cell retention times of about 4 days at 35°C (McCarty 1966, Lawrence and McCarty 1969). The above principles were later applied in the development of other anaerobic treatment processes. One process is similar to the aerobic trickling-filter process and was termed the "anaerobic filter" by Young and McCarty (1969) (Fig. 4.4). This concept was extended further in the development of the "anaerobic attached film expanded bed" reactor by Switzenbaum and Jewell (1980), in which wastes pass in an upward direction through a bed of suspended media to which the bacteria attach (Fig. 4.4). The advantage of this reactor is the relative freedom from clogging, although a disadvantage is the high rate of recycle generally required to keep the media to which the bacteria are attached in suspension.

Another development by Lettinga et al. (1979) is a similar process, which incorporates a different mode of separation of gas and suspended solids. In this "upflow anaerobic sludge blanket" reactor (Fig. 4.4), the greater surface area between the gas and the liquid that is afforded is advantageous in keeping the floating solids from clogging gas ports. A requirement of this system is that granular particles containing

bacteria be developed that settle well, and can be mixed thoroughly by the circulating gas.

[Figure 4.4: Stationary-bed and expanded-bed fixed-film reactors (From McCarty 1982)](#)

[Figure 4.5: Rotating and baffled reactors (From McCarty 1982)](#)

Rotating biological reactors (Fig. 4.5) have also been used for anaerobic treatment of wastewaters, and offer some promise (Friedman et al. 1980). The wastewater passes over and under baffles. The solids containing bacteria rise and fall, but horizontal movement through the reactor is impeded. Thus the bacteria tend to stay in the reactor. The large surface area available between the liquid and gas is also advantageous for reducing separation problems with floating solids. This reactor has not been tried yet on a large scale.

Methane fermentation is an important natural process that is responsible for the overall decomposition of natural organic materials residing in anaerobic environments. Its fundamental understanding is far from complete. Over the last 100 years, during which methane fermentation has been used for waste treatment and fuel production, several processes have been developed, each having its own potential for treatment of industrial, agricultural or municipal wastes, with a variety of organic concentrations and characteristics. Because of the varied wastes and treatment needs, it is doubtful whether any one of the many processes now available will come to dominate significantly over the others, and even the septic tank will continue to have its place. Growing experience will no doubt lead to other designs with improved performance for given situations. In addition, recent advances in fundamental understanding of the process have yet to be translated into practical application for process design, efficiency and control.

Microbial metabolism in anaerobic digestion

Effective biodegradation of organic wastes into methane requires the coordinated metabolic activities of different microbial populations. The intermediary metabolism of multi- carbon and uni- and all-carbon transforming bacteria is described in mono and co-culture fermentations. The results of physiological and biochemical experiments are presented in order to explain the fundamentals of mixed culture metabolism, and to identify key control parameters which influence the rate of organic degradation, the yield of reduced metabolites, and thermodynamic efficiency in the anaerobic digestion process.

Effective digestion of organic matter requires the combined and coordinated metabolism of different kinds of carbon catabolizing, anaerobic bacteria. Four different types of bacteria have been isolated from anaerobic digesters and their function in anaerobic digestion is illustrated in Fig. 4.6. The methanogenic bacteria perform an important role in anaerobic digestion because their unique metabolism controls the rate of organic degradation and directs the flow of carbon and electrons, by removing toxic intermediary metabolites, and by enhancing thermodynamic efficiency of interspecies intermediary metabolism

(Moigno 1882). In order to understand the intermediary metabolism of anaerobic digestion examination is needed of the metabolic factors that control: the rate of organic degradation, the flow of carbon and electrons, thermodynamic efficiency in pure and mixed culture, and the bacteria associated with biogas production. This fundamental examination also identifies several control parameters that can be engineered to improve methanogenesis and anaerobic digestion processes. The data reviewed here will be limited to recent studies.

Figure 4.6: Anaerobic breakdown of complex organic matter. Primary: hydrolytic and fermentative processe (---); Secondary: acetogenic processes (--); Tertiary: methanogehic processes (.....). (Adopted from Large 1983)

Methanogenic bacteria

Methanogenic bacteria are a very diverse group of bacteria, morphologically and macromolecularly (i.e., cell wall, lipid and DNA composition). Detailed studies on their intermediary metabolism have been limited to those of just two species, Methanobacterium thermoautotronhicum and Methanosarcina barker) (lmhoff 1938). M. thermoautotrophicum is the more prolific methanogen, but has a limited substrate range and grows with a 2 hour doubling time on H_2/CO_2, or grows very slowly on carbon monoxide alone. M. barker) is the more metabolically diverse methanogen, and it grows readily on H_2/CO_2, methanol or methylamine, but slowly with acetate or carbon monoxide as sole energy source (ibid.).

The utilization of organic nutrients by these species is not well defined; however, M. thermoautotrophicum can use cysteine as the sole sulfur source (ibid.). Both species appear to conserve energy during growth by chemi-osmotically coupling the redox reactions of electron transport to generate a proton motive force that drives ATP synthesis (Imhoff 1938). In this regard, the transmembrane potential (i.e., pH) of MN barker) is 2.2 ± 0.2 units (equivalent to 132 mv at 30°C) during methanol metabolism (Hyde 1938).

Growth curves for M. barker), culturally adapted, via sequential transfer from methanol medium, to grow on acetate as sole carbon and energy source, are shown in Fig. 4.7 . The doubling time of the acetate adapted strain is much faster on methanol (19 hours) than on acetate (49 hours). Clearly, acetate metabolism is a rate-limiting step for growth of M. barker). Notably, significant consumption of acetate continued long after the culture entered the stationary phase of growth. Cell yields for acetate and methanol calculated during exponential growth were similar (=3.9 g/mol substrate consumed), indicating a similar mechanism of energy conservation for both substrates. During growth of the acetate adapted strain of M. barker), on a mineral medium with acetate as the sole carbon and electron source, ^{14}C-2 acetate was transformed to both $^{14}CO_2$ and $^{14}CH_4$ at significant rates, during the entire time (Buswell

and Hatfield 1938). The ratio of CH_4 to CO_2 formed was close to unity. Furthermore, both ^{14}C-1 and ^{14}C-2 acetate were converted to $^{14}CH_4$ and $^{14}CO_2$. Approximately 14% of the CO_2 produced during the course of acetate fermentation, originated from the methyl carbon or acetate, and 14% of the methane produced originated from the carboxyl position. Conversely, 86% of, the CO_2 was produced from the carboxyl of acetate and 86% of the methane was produced from the methyl moiety.

M. barkeri is capable of simultaneously metabolizing both acetate and methanol. At 50 mM concentration of either substrate, the rate constants for mixotrophic methanogenesis from acetate and methanol notably increased over that observed for unitrophic metabolism of 50 mM substrates alone. In addition, methanol dramatically increased the rate of CO_2 production from ^{14}C-2 acetate, a phenomenon reported by several other investigators. Higher concentrations of methanol (i.e., 150 mM) appeared toxic, and inhibited the rate of methanogenesis from both methanol and acetate. Clearly, acetate metabolism of M. barker) is not catabolically repressed by methanol, but rather the organism gains significant metabolic efficiency and enhanced rates of methanogenesis, via simultaneous metabolism of both substrates.

Figure 4.7: Unitrophic fermentation of methanol (A) and acetate (B) by M. barkeri (acetate adapted strain) (from Buswell and Neave 1930)

Figure 4.8: Hypothetical carbon flow model consistent with unitrophic acetate catabolism by Methanosarcina barker) (acetate adapted strain). Numbers in parentheses represent fraction of molar catabolic carbon flow. X and X2 represent methyl carriers. Y is a formyl intermediate. Approximately 85% of acetate is decarboxylated to CH_4 and CO_2. 15% is catabolized via a pathway involving the oxidation of the methyl group and reduction of the carboxyl to CH_4. The addition of methanol leads to increased oxidation of C-2 acetate and oxidation of methanol via the same pathway (from Buswell and Heave 1930).

Figure 4.8 illustrates a carbon flow model for acetate catabolism of M. barkeri which could account for the results observed above. This hypothetical scheme postulates a unified pathway for metabolism of acetate and methanol that employs carrier-bound monocarbon moieties, in lieu of free carbon intermediates. Initial methanol and acetate transformations are associated with different methyl carriers. This unified oxidation pathway can explain the increase in the production of CO_2 from C-2 acetate in the presence of methanol. The numbers in parenthesis are the values for fractions of total carbon balance during unitrophic growth on acetate. Two routes for the production of methane are possible. The first is consistent with that described by Parker (1956) and accounts for 95% of the methane produced. The second is a redox process involving the oxidation of C-2 acetate and the reduction of either a formyl intermediate or CO_2 to CH_4. The very high levels of CO dehydrogenase, in the acetate-adapted strain of

MN barker). supports a catabolic function for the enzyme. In light of these findings and the work of Thauer et al. (1977), indicating that CO dehydrogenase is a B_{12} associated enzyme, it is tempting here to support the suggestion of Stadtman (1967) that B_{12} may function as a methyl carrier during methanogenesis by M. barkeri.

Homo-acetogenic bacterial metabolism

Homo-acetogenic bacteria possess high thermodynamic efficiencies of metabolism, as a consequence of not forming H_2 and CO_2 during growth on multi-carbon compounds. The intermediary metabolism of homo-acetogens is only well detailed in Clostridium thermo-aceticum, which is generally regarded as incapable of growth on monocarbon compounds alone. Butyribactearium methylotrophicum appears as a special kind of homo-acetogen, because it grows on a variety of multi-carbon compounds (e.g., hexoses, lactic acid, pyruvate), and on monocarbon compounds (e.g., H_2/CO_2, methanol/CO_2), but forms mixtures of butyrate and acetate on most substrates, except on H_2/CO_2, where acetate is the sole end product.

B. methylotrophicum (Marburg strain) fermentation yields acetic and not butyric acid when CO is added to the gas phase (Zeikus 1980). A strain of B. methylotrophicum (i.e., the CO strain) was selected via sequential transfer from methanol-CO medium that can grow on CO alone. The CO strain grows rapidly on CO with a 9 hour doubling time and produces CO_2 and acetate as end products. The apparent thermodynamic efficiency of CO metabolism, which is defined as the energy conserved as cells divided by the energy available for cell synthesis, is 57%. Notably, aerobic bacteria which grow on substrates with similar oxidation states as CO (e.g., formate) display a thermodynamic efficiency of about 20%.

Relatively little is known about the functional importance of homo-acetogen metabolism in anaerobic digestion, or the metabolic interactions of homo-acetogens and methanogens. Nonetheless, during growth on multiple carbon compounds (e.g., glucose), these bacteria derive more thermodynamic metabolic efficiency than hydrolytic species; and, as a consequence of not producing, but consuming, hydrogen homo-acetogens, lower the hydrogen partial pressure during anaerobic digestion. It is worthwhile to note here that E. methylotrophicum can, in co- culture with M. barker), metabolize butyrate as the sole carbon and electron donor. Hence, B. methylotrophicum can also function as a facultative hydrogen producing acetogen (Hungate 1950).

Hydrolytic and fermentative bacteria

Hydrolytic bacteria form a variety of reduced end products from the fermentation of a given substrate. One fundamental question which arises, concerns the metabolic features which control carbon and electron flow to a given reduced end product during pure culture and mixed methanogenic cultures of hydrolytic bacteria. Thermoanaerobium brockii is a representative thermophilic, hydrolytic bacterium, which ferments glucose, via the Embden Meyerhof Parnas Pathway (Bryant et al. 1967). T. brockii is an atypical hetero-lactic acid bacterium because it forms H_2, in addition to lactic acid and ethanol. The reduced end products of glucose fermentation are enzymatically formed from pyruvate, via the following mechanisms: lactate by fructose 1-6 all-phosphate (FOP) activated lactate dehydrogenase; H_2 by pyruvate ferredoxin oxidoreductase and hydrogenase; and ethanol via NADH and NADPH linked alcohol dehydrogenase (McInerney et al. 1979).

Different environmental conditions specifically modify the regulatory properties of T. brockii's enzymatic outfit, and this in turn alters the reduced end products formed and the specific growth rate (Barker 1936). The examples described below illustrate this feature of hydrolytic bacterial metabolism. During growth in glucose complex medium, T. brockii contains high intracellular levels of FDP and produces lactate as the main fermentation product. During growth on starch, the intracellular FDP concentration is much lower, and ethanol is the main product, as a consequence of a growth-rate limitation genus electron, caused by hydrolysis of starch. The addition of acetone, an endogenous acceptor reduced by the NADP-linked alcohol dehydrogenase, doubles the growth yield on glucose, and thermodynamically alters electron flow, even in the presence of high FDP, such that isopropanol is the main reduced end product, whereas, lactate, ethanol and hydrogen are only formed in trace amounts. Hydrogen is an effecter of T. brockii's intermediary metabolism. Glucose fermentation and growth are completely inhibited by 1 atmosphere of hydrogen. However, the addition of acetone dramatically increases the rate of growth during glucose fermentation, in the presence or absence of added hydrogen. The addition of M. thermosutotrophicum to T. brockii glucose fermentations dramatically increases the rate of metabolism, and alters carbon and electron flow, such that methane and acetate are made in lieu of lactate, ethanol and hydrogen.

The direction of electron flow in T. brockii fermentations is influenced by specific environmental conditions, which alter enzyme activities. Electron flow during glucose fermentation results in the generation of lactate, ethanol and H_2 as end products. Hydrogen inhibits growth and metabolism by the reverse flow of electrons and the reduction of intracellular electron carriers (i.e., ferredoxin, NAD and NADP). As a consequence, glucose can not be oxidized, because NAD is not available. The addition of excess acetone thermodynamically alters electron flow, even in the present of H_2 , and electrons are channelled to isopropanol production, in lieu of lactate, ethanol or hydrogen. The addition of a methanogen removes H_2, a toxic metabolite, and thermodynamically alters electron and carbon flow towards production of CH_4 as principal reduced end product, and acetate, as the main oxidized end product. It is worth noting that in the presence of M; thermoautotrophicum, T. brockii can function as a facultative H_2-producing acetogen, by growing on ethanol. This is accomplished via reverse electron flow from ethanol back to hydrogen, and can only be accomplished at low hydrogen partial pressures,

maintained by the methanogen.

The rate of methane production in anaerobic digesters is often limited by the rate of biopolymer destruction and/or effective metabolic interaction between hydrolytic bacteria and methanogens (Zeikus 1980a; b). Pectin is a model polymer for the study of metabolic interactions between hydrolytic bacteria and methanogens, because of its unique structure and intermediary metabolism. Pectin is a methoxylated polymer of galacturonic acid that is present in all plant biomass and in the cell wall of many algae. Pectinolytic bacteria form depolymerases that function either as hydrolases or transeliminases, and methylesterases which produce methanol. All pectinolytic bacteria examined to date including aerobic species - produce, but do not consume, methanol during the degradation of pectin (Stadtman and Barker 1949).

Methanogens are perhaps the most strictly anaerobic bacteria known (0.01 mg/l dissolved oxygen completely inhibits growth), and therefore detailed studies require the use of stringent procedures to ensure growth, in the complete absence of oxygen (Zeikus 1977). However, there are marked differences in oxygen sensitivity among the methanogens. Methanogenesis is extremely oxygen-sensitive, due to oxygen lability of certain of the methanogenic co-factors. The oxidation-reduction potential required for methanogenesis may be as low as -300 mV or even lower (Large 1983). Procedures developed by Hungate (1966, 1969) and modifications made by Bryant (1972), have proved successful for cultivation of these fastidious anaerobes. Methanogenic bacteria perform a pivotal role in anaerobic digestion (i.e. ecosystems) because their unique metabolism controls the rate of organic degradation and directs the carbon and electron flow, by removing toxic intermediary metabolites, such as H_2, and by enhancing the thermodynamic efficiency of intermediary metabolism (Zeikus 1983).

Methanogens are H_2-oxidizing anaerobes which obtain their energy by the oxidation of all-hydrogen, under anaerobic conditions, using CO_2, monocarbon organic compounds or acetate as electron acceptors (Large 1983). By their existence in anaerobic habitats, they make conditions more favourable for the primary (fermentative) and secondary (acetogenic) fermentation stages (see Fig. 4.6) by efficiently removing all-hydrogen. This phenomenon is termed interspecies hydrogen transfer.

In the presence of electron acceptors such as metal oxides [Fe(OH), MnO_2], nitrogen oxides (NO_3^-, NO_2^-), or oxidized sulfur compounds (SO_4^-, $SO_3^=$), methanogenesis may be inhibited and/or altered (Zender et al. 1982). Methanogenesis usually occurs only after these alternative electron acceptors are depleted. However, Zeikus (1983) suggests that the rate of methanogenesis depends on the relative amounts of electron acceptor (e.g. acetate versus sulphate) and donor (e.g. hydrogen) present. Thus, for example, methanogenesis of lake sediments, in the presence of excess hydrogen or acetate, continued, even with excess sulphate added (Winfrey 1977).

Interspecies hydrogen transfer

Methanogens are the terminal organisms in the microbial food chain in anaerobic habitats, where organic matter is being decomposed. In nature, the decomposition of organic matter to methane may be limited by the rate at which insoluble biopolymers are hydrolyzed (Zeikus 1977). The most notable feature of this decomposition process is that its successful operation depends on the interaction of metabolically different bacteria. Methanogens are distinguished by their ability to obtain energy from the oxidation of H_2 coupled with the reduction of CO_2 to methane (Main et al 1977). They may thus function as an "electron sink" during the metabolism of complex organic matter in organotrophic ecosystems, by altering electron flow in the direction of hydrogen production by non-methanogenic organisms. The non-methanogenic bacteria affected share the characteristic of H_2 formation by proton reduction, either solely, or as a supplement to the formation of reduced organic end-products for disposing of electrons generated during their respective fermentation. This interaction between H_2-oxidizing and H_2-reducing organisms has been termed "interspecies hydrogen transfer" (Iannotti et al. 1973; Wolin 1974). This term is used to describe the coupled oxidation reduction reactions between two or more interacting anaerobic bacteria during the fermentation of one initial substrate.

Interspecies hydrogen transfer occurs when the flow of fermentation -generated electrons is shifted from the formation of reduced organic end products to proton reduction. H_2 formation then becomes the major, if not sole, electron sink. Because of the thermodynamic or inhibitory properties of the reaction, such a shift in electron flow requires a mechanism for the continuous removal of H_2. This can be provided by the methanogenic bacteria (Iannotti et al. 1973). Thus, H_2 concentration (i.e. partial pressure) plays a key role in the regulation of the proportions of various end-products produced during the overall conversion of organic matter to methane. The actual amount of H_2 may be a good indicator of the course of the fermentation.

Two general categories of interspecies hydrogen transfer interactions have been demonstrated (Main 1983):
a) Interaction between methanogens and fermentative bacteria;
b) Interactions between methanogens and acetogenic bacteria.

The methanogens - distribution and taxonomy

The distribution and activity of methanogenic bacteria in nature are restricted to anoxic environments, where associated bacteria maintain a low redox potential, and produce methanogenic substrates, as well as other nutrient factors (Main et al. 1977). Organotrophic ecosystems in which methanogens have been detected include the rumen and gastrointestinal tract of man and animals, in particular herbivores,

anaerobic digesters, landfills and sediments (ponds, marshes, swamps, lakes and oceans). Methanogenic bacteria have even been found inside the heart wood of living trees (Zeikus and Ward 1974) and in hot springs, e.g. Yellowstone National Park (Zeikus 1977).

The methanogenic bacteria are unique among prokaryotes because they produce methane as the major product of anaerobic metabolism. However, morphologically methanogens are a diverse group of bacteria which include forms such as rods, spirilla, cocci, and various arrangements of these shapes into longer chains or aggregates (Main and Smith 1981).

The dilemma of a similar physiology, but diverse morphology, of methanogens was recently solved after a major revision of their taxonomy, based on comparative biochemical studies of their 16s rRNA sequences, DNA sequence, cell wall and lipids (Blach et al. 1979). It has been proposed (Woese et al. 1978), and later largely accepted, that a separate primary kingdom or ur-kingdom be recognized among the prokaryotes, to include the methanogens, the extreme halophiles and thermo-acidophiles. This proposed ur-kingdom was termed the archaebacteria (Fig. 4.9). All the remaining bacteria, cyanobacteria and mycoplasmas would belong to the urkingdom eubacteria. Eukaryotic organisms belong to the urakaryotic ur-kingdom (see Fig. 4.9).

The archaebacteria are indeed unusual organisms. The group is now known to include three very different kinds of bacteria: methanogens, extreme halophiles and thermo-acidophiles.

The extreme halophiles are bacteria that required a high concentration of salt to survive; some of them grow readily in saturated brine. They can give a red colour to evaporation ponds and can discolour and spoil salted fish. The extreme halophiles grow in salty habitats along the ocean borders and in inland waters, such as the Great Salt Lake and Dead Sea. Although the extreme halophiles have been studied for a long time, they have recently become of particular interest for two reasons: they maintain large gradients in the concentration of certain ions across their cell membrane, and exploit the gradient to move a variety of substances into and out of the cell. In addition, the extreme halophiles have a comparatively simple photosynthetic mechanism, based, not on chlorophyll, but on a membrane-bound pigment, bacterial rhodopsin, that is remarkably like one of the visual pigments (Oren 1983).

Fig. 4.9: The primary kingdoms as proposed by Woese (1978): eukaryotes, eubacteria and archaebacteria. Methanogens belong to archaebacteria.

Methanogens in hypersaline environments

Little is known on the extent of anaerobic degradation of organic matter in hypersaline environments. The sediments of hypersaline water bodies are generally anaerobic, partly as a result of biological activity in the sediments and the overlaying water, and also because of the limited solubility of oxygen in hypersaline brine. The biology of anaerobic hypersaline environments has been relatively little

studied, though it is curious to note that the first bacteria ever isolated from the hypersaline environment (though not halophilic ones), Clostridia, causing tetanus and gas gangrene, was isolated by Lortet from Dead Sea mat in the end of the 19th Century (Oren 1983).

In the reports of Zhilina (1983; 1986) in USSR and Australia, and Brooks et al. in the Gulf of Mexico (1979) methanogenesis is ascribed to the utilization of methanol, mono-methylamine, dimethylamine, trimethylamine and methionine as a carbon and energy source. Hydrogen, acetate and formate stimulated methanogenesis only "lightly, or not at all, in these cultures. However, methanogenic activity was reported in enrichments of mat sediments from the hypersaline Solar Lake, Sinai (Yu and Hungate 1983; Giani et al. 1984), where the predominant species enriched was a Methanosarcina sp., which preferentially utilized mono- methylamine among H_2/CO_2, the methylated amine and acetate. The optimal salt concentration of pure methanogens in most of the reports ranges from 7% - 15% (as NaCl).

Dosoretz and Marchaim (1990) examined the sediment and mass of water from a natural hypersaline sulfur spring on the western shore of the Dead Sea, near Ein Gedi, for the presence of methanogenic bacteria. They succeeded in collecting bubbles of biogas from the ponds and methane was found in significant quantities (9 - 15% of the total gas phase). They isolated a stable halophilic methanogenic enrichment culture which is able to utilize trimethylamine (TRI) and methanol (MET) as a preferential carbon and energy source. Mono-methylamine (MET) was moderately metabolized (Fig. 4.10). H_2/CO_2, dimethylamine (DI), formate and acetate cannot support growth. This culture grew and produced methane in a wide range of salt concentrations (80 g/1 up to 250 g/l) (Fig.4.11). Complete inhibition was found at salt concentrations higher than 180 g/l. Due to the conditions of the enrichment and the presence of H_2S, as reducing agent, no sulphate reducing activity was detected. Microscopic observation showed that the enrichment was composed only of cocci, which resemble the pure strain Methonococcus halonhilus. Furthermore, the complete coincidence between CH_4 and CO_2 formation and A_{600} found (Dosoretz and Marchaim, 1990) indicates that methanogens are the main species in this culture. The culture is very stable and it was maintained for a long period of time.

Figure 4.10: Methane production (at 37°C in μmole/ml broth) of Halophiles growth on several substances as function of days of culture growth.

Figure 4.11: Methane production (at 37°C in μmole/ml broth) of Halophiles in several salt concentrations (g/l) of which 25 g/l of other salts than NaCl has been added, as function of days of culture growth.

Influence of high salt levels on methanogenic digestion

High salt levels cause bacterial cells to dehydrate because of osmotic pressure. Some microorganisms

are more susceptible to osmotic pressure than others. Staphylococcus aureus is able to grow in solutions containing up to 65 g/l NaCl, while E. cold is inhibited at much lower levels (Brock 1970). Methanogenesis in marine or salt marsh sediments, which contain approx. 35 g/l NaCl, has been fairly well documented, mostly in relation to sulphate reduction (Abram and Nedwell 1978; Mountfourt et al. 1980). Mountfourt et al. (1980) found production rates of up to 20 ml of methane per kg of marine sediment per day at 30°C.

The inhibitory effect of sodium has been investigated by Kungelman and McCarty (1965). As compared to other metal cations, sodium proved to be the strongest inhibitor on a molar basis. Sodium showed moderate inhibition at 3.5 - 5.5 g/l and strong inhibition at 8 g/l. Van den Heuvel et al. (1981) studied anaerobic upflow digestion on acidified brine coming from the reverse osmosistreatment of sewage. The brine contained 2.1 g/l Cl$^-$, and this concentration did not pose any problems for the anaerobic upflow treatment at 20°C.

The effect of high levels of NaCl and NH$_4$Cl on the activity and attachment of methanogenic associations, in semi-continuous flow-through reactor systems, has been evaluated (De Baere 1984). Two well-functioning reactors received shock concentrations of NaCl and NH$_4$Cl while two other reactors were adapted to increasing levels of the salts during a period of 45 days. The methanogenic associations, grown on a medium containing mainly acetate and ethanol, were found to be more resistant to NaCl and NH4Cl than previously reported. Initial inhibition occurred at shock treatments of 30 g/l for both salts. The reactors, which were gradually exposed to increasing levels of the salts, adapted well and their tolerance levels surpassed those of the non-trained counterparts. Initial inhibition and fifty percent inhibition was observed at 65 and 95 g/l respectively for adaptation to NaCl. Initial inhibition for the reactor adapting to NH$_4$Cl occurred at 30 g/l and a 50% inhibition was observed at 45 g/l NH$_4$ Cl. For the reactors receiving NH$_4$Cl, the free ammonia-N should be kept below a concentration of 80-100 mg/l for optimal performance. The bacterial populations in the reactors consisted mostly out of Methanosarcina (>99% of the biomass).

Growth substrates of methanogenic bacteria

Substrates used by methanogenic bacteria as carbon and energy source include H$_2$/CO$_2$, formate, methanol, methylamines, CO and acetate. Most methanogens can grow on H$_2$/CO$_2$. However, several species are unable to metabolize H$_2$/CO$_2$. For example Methanococcoides methylutens grows only on methylamines or methanol (Sowers and Ferry 1983). Methanosarcina TM-1 (Zinder and Mah 1979), Methanotrix soehugenii (Huser et al. 1982) and Methanolobus tindarius (Konig and Stetter 1982) can grow on methanol or methylamines. About half the genera can metabolize formate, by first oxidizing it by formate dehydrogenase to H$_2$ + CO$_2$, and then by reducing CO$_2$ to methane (Daniels et al. 1984).

Methanosarcina barker) is the most metabolically versatile specie and can grow on acetate, methanol, methylamines and H_2/CO_2, but cannot grow on formate (Main and Smith 1981). In contrast to acetate which was considered the major methanogenic precursor in several ecosystems (Zeikus 1977), methanol is not considered a natural intermediate in the degradation of most organic compounds in ecosystems (Hashimoto et al. 1980). Some methanogens can oxidize CO and convert it to methane, and a few strains can use CO as the sole growth substrate (Zeikus 1983).

As mentioned above, M. barker) can grow on more than one substrate. Certain interesting metabolic traits were demonstrated in mixotrophic studies. When grown on acetate under nitrogen gas, about 80% of the methane arose from acetate, the remainder originating from organic compounds in the medium. If excess H_2/CO_2 was also present (in place of N_2), methane arose predominantly from CO_2, while in the presence of methanol and acetate (under N_2 in the gas phase) the methane produced arose from methanol. In this case, methanol stimulates oxidation of the acetate methyl group to CO_2; i.e. acetate provides a source for electrons, for the reduction of methanol, and provides little methanogenic carbon (Zeikus 1983; Kryzcki et al. 1982).

Studies of anaerobic digestion showed that, in most ecosystems (including anaerobic digesters, aquatic sediments, black mud, marshes, swamps and other non-gastrointestinal environments), 70% or more of the methane formed is derived from acetate, depending of the type of starting organic carbon. Thus, acetate is the key intermediate in the overall fermentation of these ecosystems (Main et al. 1977). In theory, only 33% of the methane can be produced from CO_2 reduction by the H_2 generated during dissimilation of the starting organic substrate to the level of acetate. In contrast, in ruminants where acetic acid, as well as propionic and butyric acids, is removed by absorption through the rumen wall and then metabolized by the host, methane appears to be almost exclusively produced from the reduction of CO_2 by H_2 (Main et al. 1977). Growth on CO_2 as carbon source is autotrophy, but the autotrophic growth of methanogens is totally different from that of virtual phototrophs and chemo-autotrophs, because it does not involve the ribulose biphosphate-Calvin cycle (Hemming and Blotevogel 1985).

Nutritional and physiological requirements

The nutritional requirements of methanogens range from simple to complex. With regard to carbon assimilation, some methanogens are autotrophs (inorganic carbon source metabolizers), some heterotrophs (organic carbon source metabolizers), and some mixotrophs (organic and inorganic carbon source metabolizers). In natural habitats, methanogenic bacteria depend strongly on other bacteria to supply essential nutrient such as trace minerals, vitamins, acetate, amino acids or other growth factors (Main and Smith 1981).

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Environmental factors which influence biological reactions, such as pH, temperature, nutrients and inhibitors concentrations, are amenable to external control in the anaerobic digestion process.

pH: Acetate and fatty acids produced during digestion (Fig 4.12) tend to lower the pH of digester liquor. However, the ion bicarbonate equilibrium of the carbon dioxide in the digester exerts substantial resistance to pH change. This resistance, known as buffer capacity, is quantified by the amount of strong acid (or alkali) added to the solution in order to bring about a change in pH. Thus the presence of bicarbonate helps prevent adverse effects on microorganisms (methanogens) which would result from low pH caused by excessive production of fatty acids during digestion. Proteins and other organic compounds, as well as bicarbonate, take a part in the buffering capacity and the resistance to changes in pH.

Most microorganisms grow best under neutral pH conditions, since other pH values may adversely affect metabolism by altering the chemical equilibrium of enzymatic reactions, or by actually destroying the enzymes. The methanogenic group of organisms is the most pH sensitive. Low pH can cause the chain of biological reactions in digestion to cease.

Fig. 4.12: Concentrations of volatile fatty acids during digestion when the pH level was kept constant by adding CaO during the entire experiment (Marchaim and Krause 1991).

There are two main operational methods for correcting an unbalanced, low pH condition in a digester. The first approach is to stop the feed and allow the methanogenic population time to reduce the fatty acid concentration and thus raise the pH to an acceptable level of at least 6.8. Stopping the feed also slows the activity of the fermentative bacteria and thus reduces acid production. Once the pH returns to normal, feeding can be recommenced at reduced levels, and then increased gradually, so as to avoid further drops in the pH. A second method involves the addition of chemicals to raise the pH and provide additional buffer capacity. An advantage of chemical addition is that the pH can be stabilized immediately, and the unbalanced populations allowed to correct themselves more quickly. Calcium hydroxide (lime) is often used. Sodium carbonate (soda ash), while more expensive, can prevent calcium carbonate precipitation.

Temperature: The metabolic and growth rates of chemical and biochemical reactions tend to increase with temperature, within the temperature tolerances of the microorganisms. Too high a temperature, however, will cause the metabolic rate to decline, due to degradation (denaturation) of enzymes which

are critical to the life of the cell. Microorganisms exhibit optimal growth and metabolic rates within a well defined range of temperatures, which is specific to each species, particularly at the upper limit which, is defined by the thermos/ability of the protein molecules synthesized by each particular type of organism.

Methanogenic bacteria are more sensitive to changes in temperature than other organisms present in digesters. This is due to the faster growth rate of the other groups, such as the acetogens, which can achieve substantial catabolism even at low temperatures (Schmid and Lipper 1969). All bacterial populations in digesters are fairly resistant to short-term temperature upsets, up to about two hours, and return rapidly to normal gas production rates when the temperature is restored. However, numerous or prolonged temperature drops can result in unbalanced populations, and lead to the low pH problems discussed above. Temperature variations can have adverse affects on mesophilic (35°C) digestion, or thermophilic (55°C) digestion. The temperature effect also depends significantly on the solids concentration of the fermentation. When high concentrations of organic loading were used (over 10%), the tolerance for changes of 5 - 10°C is much higher, and bacterial activity returns quickly when the temperature is raised again (Marchaim 1983). Two distinct temperature regions for digestion have been noted: optimal digestion occurs at about 35°C (mesophilic range) and 55°C (thermophilic range), with decreased activity at around 45°C. This response to temperature may be due to effects on methanogenic bacteria, since these appear to exhibit similar optimal regions (Fig. 4.13).

[Fig. 4.13: The Effect of Temperature on Methanogens. (After Zehnder and Wuhrman 1977; Huser et al. 1982.)](#)

Well defined mesophilic and thermophilic regions have been noted for activated "fudge and refuse feedstocks (Marina 1961; Pfeffer 1974). For beef cattle manure, raw sewage sludge, and some agricultural residues, the regions are generally the same, although not so well defined (Goluake 1958; Chen et al. 1980; Nelson et al. 1939).

An advantage of thermophilic digestion is that the rate of methane production is approximately twice that of mesophilic digestion, so reactors can be half the volume of mesophilic digesters, and still deal with the same volume of material, while maintaining the same gas production. Strong, warm, soluble industrial wastes give specific gas yields (volume of gas per volume of digester per day) of up to 8 volumes of gas per volume of digester per day with immobilized cell designs. With warm (>55°C) wastes this has obvious advantages. However, with wastes which are at ambient temperatures, such an animal manures, considerable energy is needed to raise the temperature of the waste to 55°C. A number of detailed studies of gas yields and energy consumption have been carried out (Shelef et al. 1980; Converse et al. 1977; Schellenbach 1980; Hashimoto et al. 1981).

Shelef et al. (1980) found that thermophilic digesters could accept higher organic loads than mesophilic systems at the same HRT. This advantage became more pronounced as the retention time decreased. With cattle manure at 12% total solids and HRT of 6 days, they obtained specific yields of 5.5, versus 3.0 in mesophilic digesters, and found that only 20% of the energy produced was used for heating and

mixing.

However, Converse et al. (1977), using dairy manure of 15.8% total solids, found that thermophilic operation (HRT = 6.29, T = 60°C) gave lower net energy yields than mesophilic operation (HRT = 10.4, T = 35°C). Schellenbach (1980) concluded that mesophilic cultures gave a higher methane yield per pound of volatile solids than thermophilic, and that thermophilic cultures were more unstable and sensitive to mechanical or operational disruptions. This point has been raised by a number of researchers, although there is disagreement as to how unstable thermophilic digestion is. Full scale mechanically stirred thermophilic systems of 2 - 3% solids content require temperature controls of ±0.5° C, while mesophilic systems tolerate variations of ±2°C (Gerber 1954, 1975, 1977). On the other hand, when over 10% solids are fermented, a much wider range of temperature controls are needed in thermophilic digestion (Marchaim 1983). Hashimoto et al. (1981) concluded that thermophilic digestion gave a higher net energy production per unit of capital cost than mesophilic digestion. Excellent results were obtained with an influent concentration of 8 - 10% volatile solids and detention times of 4 - 5 days. Marchaim (1983) and Shelef et al. (1980, 1983), in Israel, showed that up to 16% solids concentration can be loaded to commercial systems (of 200 m^3) with small effects on temperature changes.

In a number of papers, published recently, the "psychrophilic digestion" - digestion in temperatures of 10° 25°C, is reported (Wellinger 1989; Paris et al. 1988). Using the UASB- reactor, it could be demonstrated that, at temperatures as low as 10°C, digestion was successful (Grin et al 1985; Lettinga 1983; Verstraete 1986). The start-up of low-temperature digestion is one of the major constraints for the application of this technique. When longer retention time are used, with special attention to keeping volatile acids concentration low (Zeeman et al. 1988; Wellinger 1989), and using a mesophilic inoculum at temperatures higher than 20°C, the psychrophilic process can be successfully operated. This success in anaerobic digestion at low temperatures may alter the attitude of many farmers and factories to working with anaerobic digestion in cold countries. De Man et al. (1988) showed in a recent publication that anaerobic digestion systems (EGSB and UASB) can operate at temperatures as low as 8°C, when low strength soluble wastewaters were treated.

Nutrient Effects: In addition to an organic carbon energy source, anaerobic bacteria appear to have relatively simple nutrient requirements, which include nitrogen, phosphorus, magnesium, sodium, manganese, calcium, and cobalt (Speece and McCarty 1964). Nutrient levels should be at least in excess of the optimal concentrations needed by the methanogenic bacteria, since these are the most severely inhibited by slight nutrient deficiencies. Nutrient additions are often required in order to permit growth in digestion of industrial wastes and crop residues. However, nutrient deficiency should not be a problem with most manures and complex feedstocks, since these substrates usually provide more than sufficient quantities.

An essential nutrient can become toxic to organisms if its concentration in the substrate becomes too great. In the case of nitrogen, it is particularly important to maintain an optimal level to achieve good digester performance without toxic effects. The imbalance between the high nitrogen content and the carbon source cause toxicity by generating ammonia.

Influence of carbon/nitrogen ratio on digestion

Nitrogen present in the feedstock has two benefits: (a) it provides an essential element for synthesis of amino acids, proteins and nucleic acids; and (b) it is converted to ammonia which, as a strong base, neutralizes the volatile acids produced by fermentative bacteria, and thus helps maintain neutral pH conditions essential for cell growth. An overabundance of nitrogen in the substrate can lead to excessive ammonia formation, resulting in toxic effects. Thus, it is important that the proper amount of nitrogen be in the feedstock, to avoid either nutrient limitation (too little nitrogen) or ammonia toxicity (too much nitrogen). The composition of the organic matter added to a digestion system has an important role on the growth rate of the anaerobic bacteria and the production of biogas.

The components of the feedstock are utilized selectively by different bacteria present in the digester. This is especially true with different ratios of organic matter to nitrogen. Bacteria need a suitable ratio of carbon to nitrogen for their metabolic processes. C:N (carbon to total nitrogen) ratios higher than 23:1 were found to be unsuitable for optimal digestion, and ratios lower than 10:1 were found to be inhibitory, in studies on thermophilic anaerobic digestion of poultry manure, cow manure and mixtures of manures with paper or cellulosic materials (Kimchie, 1984). The experiments were performed with urea as a nitrogen source. Several reports examined the inhibitory effect: Hashimoto (1986) examined the effect in mesophilic and thermophilic conditions for over ten volume turnovers, and examined acclimation conditions and correlation to total volatile acids (VFA) concentrations. Velsen (1979) reported that nitrogen concentrations as high as 5000 mg/l can be tolerated by sewage sludge methanogens; and De Baere et al. (1984) reported initial signs of inhibition at about 8000 mg/l. Various studies have shown that free ammonia is far more toxic than the ammonium ion. Wiegant and Zeeman (1986) recently proposed a scheme for the inhibition of thermophilic methane digestion by high ammonia concentration. Ammonia acts as a strong inhibitor of the formation of methane from H_2 and CO_2. It has only a minor effect on the formation of methane from acetate. The inhibition of the hydrogen consumption leads to an inhibition of propionate breakdown, which acts as an inhibitor of the acetate consuming methanogens. Schwartz (1986) examined the ammonia stress on bacteria in an anaerobic sludge blanket reactor, and concluded that the high concentration of ammonia caused inhibition of anaerobic activity, but did not result in irreversible damage to the biomass in the reactor.

All the above experiments were performed with diluted cow manure (around 2.5 - 4% VS) to which NH_4Cl was added. The carbon/nitrogen (C/N) ratio of the feedstock has been found to be a useful parameter in evaluating these effects, and in providing optimal nitrogen levels. A C/N ratio of 30 is often cited as optimal (Fry 1975; NAS 1977; BORDA 1980; UNEP 1981; Kimchie 1984; Marchaim 1989). Since not all of the carbon and nitrogen in the feedstock are available to be used for digestion, the actual available C/N ratio is a function of feedstock characteristics and digestion operational parameters, and overall C/N values can actually vary considerably from less than 10 to over 90, and still result in efficient digestion.

In these studies, a compound that instantly liberates ammonium (NH_4^+) or ammonia (NH_3) was used. From their results, it was concluded that the effect of adding NH_4^+ on the inhibition of biogas production was instantaneous and the systems succeeded in recovering from the inhibition only in a few cases. In these experiments, inorganic nitrogen was used and in low organic loadings.

In order to examine whether the high organic loading in a thermophilic anaerobic digestion system has a vital influence on gas production in the presence of ammonia and organic nitrogen, the addition of NH4Cl to high organic loading systems, and the addition of blood in thermophilic conditions were examined. Thermophilic anaerobic digestion of rumen content from cattle, with and without the addition of nitrogen, as ammonium chloride or blood, to a C:N ratio of 14.3:1, did not show inhibition or improvement of biogas production (Marchaim 1989). When ammonium chloride was added, in addition to blood, to a C:N ratio of 10.6:1, biogas production began to decline sharply. When only blood was added (without ammonium chloride) to a C:N ratio of 11.1:1, no inhibition of biogas production occurred. After an electrical breakdown of several hours, which stopped mixing and heating, even the mixtures that contained blood without ammonium chloride showed a decline of gas production, from which the systems could recover to normal gas production. In the systems which contained NH_4Cl the biogas production stopped completely.

High organic loading values, which caused higher buffer capacity and organic nitrogen levels, and avoiding a sudden high ammonia concentration, were the main explanation for not experiencing inhibition under regular conditions. The main reason for changes in gas production with time depended largely on the origin and composition of the rumen content.

In contrast to assumptions based on the literature, inhibition of the thermophilic digestion process, due to the addition of NH_4^+ was not found at these high concentrations. One may think that the higher organic loading used for digestion (around 10% in added material, in comparison with 2 - 6% in others' work (Kimchie 1984, Hashimoto, 1986; Wiegant and Zeeman 1986) is the main factor in balancing the ammonia effect. Since inhibition was found to be caused by NH_3 and not by NH_4^+ (Wiegant and Zeeman 1986) the influence of buffer capacity, caused by high organic loadings, is of major importance.

Toxicity Effects: Anaerobic fermentation has a reputation of being sensitive to toxicants, and, moreover, methanogenesis is reported to be the most sensitive step. A common misconception about anaerobic digestion is, however, that the process cannot tolerate toxic substances, and that the biota die when exposed to toxicants. Due to the prolonged generation times, the recovery periods can be considerably extended if the toxicant is indeed bactericidal. However, studies on toxicity recovery of methanogenic strains indicate that some toxicants, found in agricultural and industrial wastes, exhibit a bacteriostatic or reversible effect on the methanogens, at the low concentrations normally encountered. Methanogenic bacteria were able to acclimatize to levels of many times those causing inhibition to unacclimatized methanogens (Speece and Parkin 1983; Speece 1985).

Environmental conditions such as pH, hydraulic retention time (HRT), total solids (TS) and organic loading rates (OLR) influence the sensitivity of bacteria, the response to toxicity and acclimatization characteristics (Hashimoto et al. 1980). For example, long HRT increases the potential for acclimatization and, in general, minimizes the severity of response to toxicity. Another important environmental factor involves toxicities of excessive quantities of many common, relatively non-toxic, organic or inorganic substances, which become inhibitory at high OLR values. The threshold toxic levels of inorganic substances vary, depending on whether these substances act singly or in combination. Certain combinations have a synergistic effect, whereas others display an antagonistic effect (Kungelman and McCarty 1965; Kungelman and Chin 1971).

Inorganic cations, such as Ca^{++}, Mg^{++}, Na^+, K^+, Fe^{++} or NH_4^+, which have a stimulatory effect at low or normal concentration, exhibit inhibitory effect at higher concentrations. Inorganic ions such as $SO_4^=$, NO_3^-, are potential inhibitors of methanogenesis in their ability to be alternative electron acceptors (Winfrey and Zeikus 1977). Sulfide (S) which is essential for most methanogens, is toxic above 200 mg/l, and made insoluble when heavy metals are present (Stafford et al. 1981; Zeikus 1977).

Toxic compounds affect digestion by slowing down the rate of metabolism at low concentrations, or by poisoning or killing the organisms at high concentrations. The methanogenic bacteria are generally the more sensitive, although all groups involved in digestion can be affected. Due to their slow growth, inhibition of the methanogens can lead to process failure in completely mixed systems, due to "washout" of the bacterial mass (i.e. the draining of bacteria through the outlet at a faster rate than their generation in the digester).

In order to control and adjust operation, to minimize toxic effects, it is important to identify inhibition in its early stages. The two main indicators of inhibition are:

a. Reduction in methane yield, indicated by two or more consecutive decreases of more than 10% in daily yield at a constant loading rate;
b. Increase in volatile acids concentration, generally occurring when the total volatile acids (expressed as acetic acid) exceed the normal range of about 250 to 500 ppm (mg/l).

The major toxicants usually encountered with natural feedstocks are ammonia, volatile acids, and heavy metals.

Ammonia: Ammonia toxicity is often a problem in feedstocks with a high protein content. Ammonia is rapidly formed in a digester, by deanimation of protein constituents. Free ammonia has been found to be much more toxic than ammonium ion, and thus ammonia toxicity thresholds are very sensitive to pH below 7.0. In general, free ammonia levels should be kept below 80 ppm, to prevent inhibition (Anderson et al. 1982). A much higher concentration, about 1,500 - 3,000 ppm ammonium ion can be tolerated (McCarty 1964a; Fischer et al. 1979; Hart 1963; Schmid and Lipper 1969). Concentrations of free ammonia and ammonium ion are related by equilibrium reactions and pH.

Volatile Acids: High concentrations of volatile acids such as acetate, propionate or butyrate, are associated with toxicity effects. It is not clear whether these acids are themselves toxic, or whether acid buildup (pH <6.8) is merely a manifestation of toxicity. Among these acids, inhibitory effects have been demonstrated only for propionate, and only at relatively high concentrations of greater than 1,000 ppm (Hobson and Shaw 1976).

Heavy Metals: Certain heavy metals are toxic to anaerobic organisms, even at low concentrations. Heavy metal ions inhibit metabolism and kill organisms by inactivating the sulfhydryl groups of their enzymes in forming mercaptides (Mosey et al. 1971). Since these reactions involve metal ions, it is the soluble fraction that is the toxic form, and toxic effects are thus affected by the solubilities of heavy metals under various digester conditions (Theis and Hayes 1979). Since many heavy metals form insoluble sulfides or hydroxides under pH conditions in the range of those found in digesters, one way to avoid heavy metal toxicity is to add chemicals such as sulphates, which will form non-toxic complexes or insoluble precipitates. Toxic substances can also be removed from the feedstock or diluted to below the toxic threshold level.

Biodegradability of digester feedstock

In general, most natural organic wastes can be digested; lignin is the major exception. In Developing Countries, the primary substrate is cattle dung, due to large cattle populations. This is a good substrate, since it is moderately degradable, and is well balanced nutritionally (C/N = 25:1).

Swine and poultry manures produce even more biogas per unit weight, and at higher rates, with lower C:N ratio and higher risk of failure of digestion operations. Human wastes (nightsoil), as well, are high in nitrogen (C/N = 6), and can also be digested. Carbohydrate wastes could be added to raise the C/N ratio and provide more gas.

Agricultural residues (e.g., wheat, rice straw) are usually readily available, but have a high C/N ratios (over 40). They can only be digested in a mixture with manures and nightsoil. These wastes are usually partially biodegradable, and can be made more so by physical size reduction, and by pre-composting. However, problems can arise with these materials because they float in the digester and form hard scum on the surface. The high lignin content of this material, which is not degradable, gives the fibrous feature to the digested slurry, used after fermentation as a soil conditioner.

Plants, such as water hyacinth, duckweed, etc., can also be degraded easily, and give quite high gas yields. In these cases, digestion of these weeds can solve the problem caused by excess weed growth in canals, while providing energy as well. Since their primary productivity is very high, the opportunity exists to create an "energy farm", by cultivating these weeds, perhaps in wastewater, which would also solve the problem of wastewater treatment. They absorb toxicants from the sewage and therefore the

digested slurry obtained is limited in its uses.

Wastes generated in urban areas (garbage, organic domestic and industrial wastes) are in principle also amenable to anaerobic digestion. However, these feedstocks have not been thoroughly explored in Developing Countries.

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Chapter five: Environmental pollution and pathogen control

Environmental pollution

The rapid growth of the world population in the past decades has resulted in two factors that are particularly relevant to us here: increased urban wastes and the intensification of agriculture.

The first has led to the creation of toxic wastelands; the second to an increase in agricultural waste products, which represent wasted resources, as well as leaching pesticides and chemical fertilizers into the soil. Both of them contribute to a new menace, whose scale is giving rise to a crisis that is on a par with the food production crisis of the 50s and 60s: the contamination of water, both surface sources and ground water. In many parts of the world, a shortage of drinking water is an actual problem, or threatens to become one very soon. It is worth noting that this problem is not dependent on the state of the affected country's development.

It is not our purpose here to discuss questions of water conservation, but to point to the contribution that anaerobic digestion can make towards a solution to the problem of land and water pollution.

The conversion of wastes to harmless and useful products can provide at least a partial answer to urban pollution, while at the same time relieving the pressure on ground water threatened by pollution. The replacement of chemical fertilizers, soil conditioning and the recycling of waste products represent the contribution of the rural sector. Fewer harmful substances will leach into the soil, and from there into sources of drinking water, while the water holding properties of the soil will be improved, saving irrigation water and thereby reducing seepage. It is, of course, well established that agriculture must limit itself to wastewater for irrigation, but even this wastewater must, in the long run, be treated to render it less pathogenic.

While the present state of development of anaerobic digestion does not offer a complete solution to land and water pollution, it already provides a partial answer, and may be the key to the solution of a problem that has overtaken that of food shortage on a world-wide scale, now and in the immediate future.

The need for decontamination

Waste products of farms, such as animal and human manures, straw and cotton wastes, as well as wastes of cattle and pig slaughtering (the manure of animals in the pre-slaughter period, the contents of the intestinal tract and other organic solids) are highly contaminated with pathogenic microorganisms and are therefore hazardous to animals and humans. When examined, pathogenic microorganisms are frequently found in the excrete of farm animals, and include enteric bacteria, fungal spores, parasite eggs and some hardy viruses. Through the practices of waste disposal by land application, these microorganisms may contaminate equipment, soil and surface water. The transmissions of pathogens present a potential threat to the health of farm workers and consumers, as well as farm animals. Prophylactic treatments, such as medication and sanitation, can help control pathogens. However, these treatments are increasingly expensive, and decreasingly effective, because drug resistance can develop in microorganisms. A mute treatment process is needed that will destroy pathogens and consequently protect environmental health. This is important, not only in the Developing Countries, where sanitary practices are inadequate, but also in the Developed Countries where animal production is so intensive that animal wastes are generated at high rates (Klinger 1986; White 1982; Shih 1988). Several papers and guidelines have been published, concerning different methods of handling manure and environmental hazards, by the FAO Network on Animal Waste Utilization.

Slaughterhouses are, inter alia, terminal stations for diseased animals. Usually sufficient care is taken to avoid a health risk to consumers of the animal products themselves, but very few precautionary measures are reported in the literature (Grant 1980) to avoid the spread of infective agents through these solid wastes. The waste of slaughterhouses is usually flushed into the municipal sewage purification system (Irmer and Belting 1984), where it creates a severe problem, due to the very high biological oxygen demand (BOD) and chemical oxygen demand (COD). Some authors consider that a slaughterhouse which processes 100 head of cattle daily produces sewage with BOD equivalent to a town of 40,000 50,000 people (Klinger 1986).

This is where a decontamination method to safeguard environmental health is necessary, particularly when dealing with a food producing establishment. Anaerobic methanogenic fermentation is an attractive method for this purpose, as it converts the waste materials into useful products. Changes in the microbiological content of the fermented material, and uses of the residual materials are discussed here.

Strict hygienic measures have to be taken in order to protect human health in the operation of slaughterhouses. Intestinal content, particularly rumen contents and the excreta of the animals, create a nuisance for sewage purification systems. Anaerobic methanogenic thermophilic digestion (Klinger and Marchaim 1987) has proved itself, not only as a process which converts part of this material into useful substances, but also as a decontamination process. The anaerobic thermophilic process reduced coliforms by 6 - 7 logarithmic units, and Salmonellae to below the regular detection level. In several cases, Salmonellae were present in the material loaded into the digester, but was reduced to below the detection level by the thermophilic fermentation.

Anaerobic digestion is both a resource and an environmental biotechnology. In the treatment of animal waste, it produces biogas as an energy source, while the digested slurry is used as a fertilizer or a feed. It decomposes organic waste to reduce environmental pollution and also destroys pathogenic microorganisms, protecting human and animal health. The multiple benefits of the system have been demonstrated on the basis of diverse waste digesters, both at North Carolina State University (Steinsberger & Shih 1984; Steinsberger et al. 1987; Shih 1987b; Shih 1988; Jiang et al. 1988), and on some Kibbutzim in Israel. By integrating the multiple benefits around the technology, a concept was proposed of holistic farming, as a new agricultural ecosystem (Marchaim 1983; Shih 1985; Shih 1987a). However, holistic farming on a large scale in Developing Countries is yet to be assessed and implemented.

The results of a series of studies, conducted in several countries to establish the role of poultry and cow waste digesters in the control of different types of microbial pathogens, are reported. The fate of pathogenic microorganisms, including Salmonellae, faecal coliforms, fungi , protozoan oocysts and viruses, in poultry waste anaerobic digesters has been studied (Shih 1988). The digesters were operated in the laboratory at thermophilic (50°C) and mesophyllic (35°C) temperatures. When comparing the influent (manure slurry) and effluent samples, it was found that faecal coliforms including Salmonellae were completely destroyed in the 50°C digester in 24 furs, and reduced by 50 - 70% at 35°C. Reductions of fungi were close to 100% at 50°C and 95% at 35°C. The digesters were inoculated with oocysts of Eimeria tenella. After 24 furs, oocysts were recovered and tested in vitro for sporulation and for infectivity, in young chicks. The thermophilically treated oocysts lost all their infectivity, while the mesophylically treated remained 40% infective. Marek's disease virus (MDV) was incubated anaerobically with digester fluid at 50°C. After 24 furs, isolation of MDV was attempted by centrifugation and its presence tested for by DNA hybridization with ^{32}p-labelled MDV gene probe, prepared from a gene library, cloned in plasma-cd $_p$BR328. No MDV DNA was detected by dot-blot hybridization. Evidently MDV were destroyed, and its DNA disappeared. In conclusion, a broad spectrum of microbial pathogens can be destroyed by anaerobic digestion, especially at thermophilic temperatures. Although the pathogens studied were related to poultry diseases, it is believed that the digestion process will also kill pathogens causing human diseases.

Enteric bacteria: Many pathogenic bacteria, including Salmonellae, Enterobacterium, were found associated with poultry, pig and cow waste samples (Alexander et al. 1968; Kraft et al. 1969; Smith et al. 1978; Shih 1988; Klinger and Marchaim 1987). These bacteria in poultry waste can be a source of contamination of poultry houses, equipment and runoff water (Kraft et al. 1969; Coker 1983; Khaleel et al. 1980; Thelin & Gifford 1983). It is of great concern that the contamination can be carried over to the final poultry product destined for consumers. The reduction of these pathogenic bacteria on the farm will not only protect the health of a poultry farm environment, but also protect the health of consumers by reducing the incidence of food contamination.

Shih (1988) compared the effects of mesophyllic (35°C) and thermophilic (50°C) poultry waste digesters on faecal coliforms including Salmonellae. Fresh manure samples collected from a commercial egg farm were used to prepare the slurry for daily feeding of laboratory digesters. The digester influent

(manure slurry) and effluent were sampled and the most probable number of Salmonella was examined (McCoy 1962). No bacterial growth on the plate was detected from the effluent of a thermophilic digester, but numerous colonies of presumptive coliforms were observed from that of a mesophyllic digester (Shih 1988). In the influent, there was an average of 1.9×10^5 presumptive total coliforms and 14.4 Salmonellae per 100 ml. In the effluents, there were 6.5×10^4 coliforms (66% reduction) and 7.0 Salmonellae (51% reduction) per 100 ml from the mesophyllic digester, but none at all were detected from the thermophilic digester.

For the examination of cow manure and slaughterhouse wastes, microbial counts were performed according to a standard method (Klinger et al. 1986). The following parameters were calculated and analyzed: total aerobic mesophyllic bacteria (TAM); total anaerobic mesophyllic bacteria (TAnM); total aerobic thermophilic bacteria (TAT); total coliform bacteria; sulphite reducing clostridia (S. Red. Cl.), and the presence of Salmonellae. Counts of bacteria were performed in duplicate. The figures presented in Table 5.1 are the mean of decimal logarithms of two counts each. Thermophilic anaerobic fermentation was selected to treat slaughterhouse wastes, because it was hoped to eliminate Salmonellae and reduce pathogenic bacteria populations. As evident from Table 5.1, there was a reduction of several orders of magnitude in coliform bacteria and, in most cases, total elimination of Salmonellae. Where fermentation was unstable or incomplete, an immediate increase of coliforms occurred, and in some cases survival of Salmonellae was observed. Few changes were observed in other bacterial parameters examined. Sulphite reducing clostridia usually survived in up to 10^3 colony forming units (CFU) per ml.

This material was also examined for its bacterial population after a month of composting. Bacterial content was similar to that of slurry (Table 5.1), but in all cases except one no Salmonellae were detected, and coliforms were reduced to below the detection level. In the one exceptional sample, a positive reaction for Salmonella was found in the fresh Peatrum used for the mushroom production.

Table 5.1: Changes in bacterial population before and after AMTD of rumen content and cow manure loaded into pilot plant.

Bacteria type	Logarithms of bacterial count					
	Material loaded			Digested Slurry output		
	mean	upper	lower	mean	upper	lower
T.A.M	6.41	7.70	5.95	5.87	6.00	5.78
T.A.T.	5.66	5.84	5.30	5.11	6.84	<5.00
T.An.M.	7.04	7.48	5.60	5.69	7.00	5.00
S.Red.Cl.	2.78	3.48	2.30	<2.00	3.00	<1.00
Coliforms	6.38	6.86	5.30	<2.30	3.00	<1.00

pH	7.10	7.50	6.50	7.46	7.60	7.20

Fungi: Many moulds, including both pathogenic and toxigenic ones, have been found in poultry, cow, pig and other wastes. They are the species of Asperaillus, Penicillium, Candida, Fusarium, Mucor, etc. Fungal spores and mouldy feeds are the main sources of contaminations. Little work has focused on the fate of fungi in animal waste treatment processes, but they were found in various sludges and effluents from municipal waste treatment plants (Butler 1960; Cooke 1965b). Two studies demonstrated that decreased crop yields could be traced to phytopathogenic fungi in sewage water used to irrigate the fields (Butler 1960; Cooke 1971). Only one study was reported on seeding pathogenic fungus into an anaerobic digester and following its viability. A 99% loss of the viability of the spore of Fusarium oxysporum was detected after 28 hours in a mesophyllic anaerobic digester (Turner et al. 1983).

In Shih's laboratory the effects of mesophyllic and thermophilic anaerobic poultry waste digesters on the resident fungi in poultry manure were studied (Woollens 1987). Destruction of fungi and fungal spores during digestion was assessed by comparing colony counts of influent and effluent of the digester. The numbers of fungi or fungal spores in the influent varied from sample to sample, but they were all drastically reduced in both digesters. In the mesophyllic digester, the reduction rate averaged 95%, and in the thermophilic digester, 99.8%.

Protozoa Parasitic protozoa, nematodes, cestodes and helminths are also of concern in waste treatment. Most of these organisms have a life cycle that includes a stage in which they are resident in the animal gut, and are thus often present in animal waste. Generally speaking, the cysts of the protozoa such as Entamoeba and Gtardia are inactivated by anaerobic digestion. The eggs of parasites such as Ascaris, Toxocara, Toxascaris and Trichuris are more resistant (Leftwich et al. 1981; Black et al. 1982; Coker 1983; Olsen 1984). The effectiveness of anaerobic digestion in destroying cysts and eggs is dependent on time and temperature. Anaerobic digestion can retard egg development, due to the lack of oxygen. Increasing temperature enhances the destruction or inactivation of parasite eggs. Anaerobic treatment at 60°C for land application was recommended (Hays 1977). In China an improvement in public health in some rural areas has been reported, after a large number of digesters were installed in the 70s (Zhao 1985).

TABLE 5.2: Decrease of Fungal Counts in Digested Poultry Waste

		CFU/ml		Reduction
		Influent	Effluent	(%)
Mesophyllic				
Exp.	1	5,386	235	96.6
	2	4,586	403	91.2

	3	13,314	396	97.0
Thermophilic				
Exp.	1	1,529	1	99.9
	2	1,671	10	99.4
	3	386	0	100.0

Coccidiosis caused by the protozoan Eimeria species is one of the most prevalent diseases of poultry. An important factor in the epidemiology of coccidiosis is the survival of oocysts which are shed in the excrete of infected hosts. A waste treatment process which destroys oocysts will interrupt the life cycle of coccidia, and thus prevent the disease (Fayer and Reid 1982). The effects of mesophyllic and thermophilic anaerobic digestion on the survival and infectivity of the oocysts of Eimeria tenella were studied by Shih (1985, 1988) and Lee and Shih (1988). Active oocysts, collected from the faecal contents of infected chicks, were found to be badly damaged after thermophilic (50°C) digestion: unable to sporulate and non-infective to young chicks. On the other hand, oocysts after mesophyllic digestion were still moderately infective.

Viruses Viral pathogens present a formidable challenge to the development of waste treatment processes. Human enteric viruses are nearly always present in sewage, and remain active in many conventional-treatments (Ward & Ashley 1976). One can predict that viruses affecting animals are present in animal waste, though little work has been done in this area. Some viruses, in their free form, are able to remain active in nature for long periods. Viruses also migrate freely in ground water. There is a potential for ground water contamination resulting from land application of waste material. Several studies have shown that human viruses such as Coxsachievirus, Poliovirus, Echovirus, and several other enteric viruses are substantially inactivated during anaerobic treatment, especially at thermophilic temperatures (Ward and Ashley 1976; Eisenhardt et al. 1977; Berg and Berman 1980). ard and Ashley (1976) listed four major factors involved in viral inactivation. They are temperature, ammonia concentration, pH, and presence of ionic detergents. The propensity of viruses to adsorb to solids in wastes is a major protective factor and prolongs their survival time when subjected to treatment processes. As anaerobic digesters are applied in agricultural waste treatment, more investigations should be conducted to determine the fate of animal viruses in these systems. Diagnostic methods for MDV infection, for instance, have been developed in some laboratories (Pyrzak and Shih 1987; Xi et al. 1986).

The role of blogas in improving rural development, environment and ecology.

In China, anaerobic digestion is an important way of making use of biomass resources, achieving a number of benefits through biogas technology, in the production of energy, the protection of the environment and improvement of the ecology. China's use of biogas technology has attracted attention in many other countries.

A biogas digester connected with a latrine and pigsty was developed in 1973, and since then many such digesters have been built in rural areas of China. Manure flows into the digester automatically, reducing exposure and loss into the air and improving environmental sanitation. Human excrete are also washed from the latrine, directly into the biogas digester. An effective way has been found to solve the problems of environmental sanitation of cities and rural areas, through biogas technology. Before biogas systems were constructed, the hygienic and sanitary conditions in the countryside were poor, in general; there was garbage, manure, pieces of straw and stalks in the farmers' courtyards, mosquitoes and flies, with occasional epidemics, which seriously threatened the health of farmers. After the building of digesters, these wastes were all put into digesters for anaerobic fermentation and gas production. In rural areas, a small digester, connected with the latrine and pigsty, was recommended and popularized. This kind of digester is a vertical cylindrical type: most of them are 6 - 8m^3 in volume. The retention time of slurry in the digester may be more than 30 days. In addition, there are digesters with capacity of hundreds of m^3 in a few state farms. An experimental latrine connected with a three-stage type biogas digester was designed and constructed in Mianyang City, Sichuan Province. By adding new sanitary installations, the latrine was freed from flies, pupae and offensive odours. (Den Ke-yun et al. 1988). The reduction in egg population in the effluent was about 95.3%. The fatality rate of Ascaris eggs was 93.7% in the effluent, 65.2% in the buffer tank, and 12.5% in the slide ditch. Colititer was 10^{-7}-10^{-5} in effluent. The result of killing parasite eggs was much better than that in an ordinary latrine, used as a control.

It is clear from the foregoing that great benefit can be obtained from the control of pathogens by fermentation; and that the anaerobic process is considerably more effective then aerobic fermentation.

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Chapter six: Aerobic versus anaerobic wastewater treatment

Until the beginning of the 20th Century, common sewage treatment was landspreading. From this, trickling filter treatment was developed. Due to the increasing amount of concentrated sewage, scientists looked for intensive treatment without the aid of filters. Since 1890, both in the U.K. and the U.S., trials were made to relieve obnoxious conditions arising from wastewater, by blowing air through the water phase. It was around 1912 that a big advance was made, not discharging the flocculent biological solids, but using them over and over again. The principle of "activated sludge" was first described by Ardern and Lockett (1914) and later by Sawyer (1965). Hence, all together, aerobic treatment is about 100 years old. Only in recent years the emphasis of aerobic wastewater treatment truly shifted from the technological hardware to the biotechnological software.

At the end of the 19th Century, the important advance towards anaerobic treatment of the suspended solids of wastewater was made. The industrial approach of sludge digestion was realized at the turn of the century in the U.K. The first heated tank was installed in 1927 in Germany (McCarty 1982). In contrast to aerobic treatment, the recognition of the biological phenomena occurring in the digestion process started at the same time as this technology came to existence.

Now that both aerobic and anaerobic wastewater treatment can be considered as having been upgraded to the level of scientific recognition, it is worthwhile to evaluate to what extent both technologies are currently evolving, either as complementary to one another, as it tended to be in the past, or as direct competitors.

A broad overview of criteria directly applicable to wastewater treatment is given in Table 6.1. Obviously, such listing is only qualitative and the choice of items listed is subjective.

The first step to improve the technology relates to the very basis of aerobic treatment, i.e. the fact that microbial biomass, after having adsorbed and partly metabolized the soluble and colloidal organics, flocculates and settles out, so that a clear effluent is obtained. Vital information on the nature of the filamentous and zoogloeal floe organisms and their ecophysiology all dates from the last decade. European research centres, in particular, have contributed to a better biotechnology of activated sludge floe formation (Chudoba et al. 1973; Eikelboom 1975; Van Den Eynde et al. 1984; Rensink et al. 1982; Slijkhuis 1983; Cech and Chudoba 1983). The concepts of "filamentstrengthened sludge floes" (Segzin et al. 1978) and "feast/famine sludge floes" (Rensink et al., 1982; Slijkhuis, 1983) now make it possible to operate activated sludges with a fair degree of insight and control (Verstraete and Van Vaerenbergh, 1986).

TABLE 6.1: Listing of Criteria Applicable to Wastewater Treatment

Criterion	Aerobic	Anaerobic
Range of water that can be treated	+	
Process stability and control		+
Volumetric loading rates applicable		+
Power input		+
Heat input	+	
Surplus "fudge production		+
No Nutrient requirements		+
No Oxygen requirement		+
Degree of BOD removal	+	
Degree of NOD or N removal	+	
Degree of P removal	+	
Production of valuable by-products		+
Chlorinated organics may be degraded	+	

Adapted from Vochten et al. (1988) = advantage over the other

Aerobic treatment

The second factor hampering aerobic wastewater biotechnology is the relatively low density of the microbial biomass in the reactor. Due to the settling problems, the amount of biomass in the mixed liquid Was to be kept in the range 3 - 5 kg volatile suspended solids/m^3 . The most obvious solution to this problem is to allow the biomass to anchor to a heavy carrier, such as sand particles, and to operate the reactor as an upflow fluidized bed. Excellent work has been done in this respect both in the USA and Europe (Shieh et al. 1979; Heijnen 1984). Biomass densities up to 30 kg/m^3 can be attained and volumetric loading rates surpassing those of conventional activated sludge by a factor of 10 can be reached accordingly. Yet practice does not yet accept this breakthrough. The reasons for this are probably two-fold. First, fluid bed technology increases the complexity of the treatment and involves the need for intensive control: conventional systems are quite simple and only controlled extensively. Second, fluid bed technology focuses on rate of removal per unit reactor volume: the major element in aerobic treatment is quality of the end-product.

A third series of changes in aerobic treatment can be grouped under the common denominator of "easier and more economic design and operation". Table 6.2 lists some recent European developments. They point to the major weaknesses of aerobic systems. Of particular interest, in this decade, is the factor of control by computer technology. A major asset of the aerobic systems is their capacity to handle all kinds of wastewaters, especially those with extremely variable composition and even, from time to time, toxic pulses. Yet, although robust, these systems can not cope with everything. Berthouex and Fan (1986) reported that even well attended aerobic wastewater treatment plants, facing no major shocks or toxic pulses, are currently not meeting the discharge standards around 20% of the time. Up to now, no on-line big-monitoring devices, capable of quantifying the incoming load and possible toxic pulses as well, and translating this information to the operation control system of the reactor continuously, have been developed. It is likely, however, that in the coming years, an advance along these lines can be expected. This will undoubtedly improve the

attractiveness of aerobic treatment in general, and of variable industrial waste-streams in particular.

TABLE 6.2: Overview of Some Recent Developments in Aerobic Wastewater Treatment Enabling Easier and More Economic Design and Operation.

Parameter	Principle involved	Reference
Improving oxygen supply	Measuring oxygen uptake rate in bypass reactor Measuring short-term BOD	Matsche et al., '76 Spanjers & Klapwijk 86 Vandebroek 1986 Siepmann 1985
Decreasing sludge	Monitoring NO_3 levels Increasing cellular maintenance by imposing pressure cycles in a deepshaft reactor	Kayser 1986 Bolton et al. 1976
Integrated control	Dynamic models relying on on-line measurements	Holmberg, 1982
Decreasing plant surface and/or construction costs	Biotower reactor systems A-B system Unitan	Zlokarnik, 1983 Bohnke, 1984 Eyben et al., 1985

A fourth series of advances relates to advanced treatment. Wastewater treatment is no longer a matter of removal of the bulk of soluble and particulate organic matter. The removal of nitrogen through nitrification and denitrification has been recognized as a process step of major importance. Indeed, by careful regulation of the oxygen supply, it is possible to have nitrification at the outside of the sludge floes, while denitrification of the nitrate thus formed prevails in the oxygen- limited inner space of the same floe (Klapwijk 1978; Barnes and Bliss 1983). In this way, not only the nitrogenous pollutant is removed in an elegant way, but also the energy invested in the nitrification step is entirely recovered, because the nitrate ion serves as alternative electron acceptor for the facultative aerobic microorganisms. Obviously, nitrogen removal through on- line regulated nitrification/ denitrification is a great asset of aerobic microbiology. The removal of phosphate, based on the special characteristics of certain aerobic bacteria to accumulate phosphorus, has been experimentally explored for about a decade (Nicholls and Osborn 1979; Rensink et al. 1979). The biological removal of mineral phosphate from wastewater appears to pose no major technical problems.

Finally, a series of approaches relating to improvement of the metabolic diversity and affinity of the aerobic microbial community should be mentioned. By providing, in the mixed liquor, matrices on which the microorganisms can colonize, one can obtain a more diverse microbial community, comprising both immobilized and free floating organisms. Some approaches along this line are the addition of polyurethane foam sponges (Cooper et al. 1984; Reimann 1964), the addition of powdered activated carbon (Betters 1979; Sublette et al. 1982), the combination of a trickling filter directly to the activated sludge process (Harrison et al. 1984) and the instalment of plastic packing in the activated sludge basin (Weber 1984).

It must be stressed that current knowledge of the ecology of activated sludge microbial communities is very limited. The model of Taylor and Williams (1975) predicts that the more diverse the composition of the feed, the more diverse the resulting microbial community will be. This model awaits experimental support, but the literature available so far suggests that, indeed, activated sludge communities are composed of a diversity of bacteria, actinomycetes, fungi and protozoa. Hence, their overall genetic pool is very large. As to the aspect of affinity, the aerobic big-film and activated

sludge organisms grow at ambient substrate levels of the order of 0.1 - 10 mg/l. Recently, insight has become available on biokinetics at such low substrate levels (Simkins and Alexander 1984). This faculty of aerobic microorganisms is also an important asset of aerobic treatment.

Anaerobic treatment

As reviewed by McCarty (1982), anaerobic digestion has existed as a technology over 100 years. It gradually evolved, from an airtight vessel and a septic tank, to a temperature-controlled, completely mixed digester, and finally to a high rate reactor, containing a density of highly active biomass. The microbiology of methane digestion has been examined intensively in the last decade. It has been established that three physiological groups of bacteria are involved in the anaerobic conversion of organic materials to methane. The first group, of hydrolyzing and fermenting bacteria, converts complex organic materials to fatty acids, alcohols, carbon dioxide, ammonia and hydrogen. The second group of hydrogen producing acetogenic bacteria converts the products of the first group into hydrogen, carbon dioxide and acetic acid. The third group consists of methane forming bacteria, converting hydrogen and carbon dioxide or acetate to methane.

In contrast to aerobic degradation, which is mainly a single species phenomenon, anaerobic degradation proceeds as a chain process, in which several sequent organisms are involved. Overall anaerobic conversion of complex substrates therefore requires the synergistic action of the micro-organisms involved. A factor of utmost importance, in the overall process, is the partial pressure of hydrogen and the thermodynamics linked to it. This fact has been recognized and discussed by researchers (Bryant et al. 1967; Boone and Bryant 1980; McInerney et al. 1979; Hickey and Switzenbaum 1988). This is also referred to in Chapter 9 on "Control".

Another factor of fundamental importance has been the identification of new methanogenic species, and the characterization of their physiological behaviour. Of particular interest was the determination of the substrate affinity constants of both hydrogenotrophic and acetotrophic methanogens. While the first exhibit quite high substrate affinities and remove hydrogen down to ppm levels, the second group appears as yet to contain species with only low substrate affinities (Zehnder et al. 1980; Huser et al. 1982). This limited substrate affinity has, of course, an important consequence for anaerobic wastewater treatment.

A technological advance of utmost importance in anaerobic digestion has been the development of methods to concentrate methanogenic biomass in the reactor, especially in very low solids concentration in the wastewater, 1 - 2%. Such higher concentration of biomass can be achieved by the principle of autoflocculation and gravity settling as, for instance, in the UASB reactor (Lettinga et al. 1983), by attachment to a static carrier (anaerobic filter) (Henze and Harremoes 1982; Van Den Berg and Kennedy 1981; Young and McCarty 1969), by attachment to a mobile carrier (fluidized bed) (Binot et Heijnen 1984; Bull et al. 1984) or by growth in and on a matrix (Huysman et al. 1983). All these different methods are in full development.

For insoluble organics, the major advance made during the past decade relates to solid state fermentation (SSF), also known as dry anaerobic composting. The work of Jewell (1979) in the U.S. revived interest in operating digesters at high levels of dry matter (up to 40%). Currently, several successful technologies to digest particulate organics at high rates, in solid state fermenters, are available (De Baere and Verstraete 1984). Of particular significance is the fact that, with systems operating in the thermophilic range (50 - 60°C), not only high volumetric conversion rates are obtained, but also a stable and hygienic endproduct, humus (De Baere et al. 1986; Deboosere et al. 1986; Marchaim 1983).

Interesting progress has also been made on direct anaerobic treatment of wastewaters at low temperatures (8 - 25°C). Reactors with granular sludge beds and with polyurethane carrier matrices have been shown to hold potential for direct

treatment of domestic wastewaters (Lettinga et al. 1983; Verstraete 1986; Lettinga et al. 1988).

Besides the advances reported above, several other developments are currently occurring in the anaerobic treatment of wastewaters. As for aerobic treatment, they are indicative of specific weak points of the technology involved. For instance, information is constantly increasing with regard to the competitiveness of methane producing bacteria (MPB), relative to sulphate reducing bacteria (SRB) (Zaid et al. 1986a, b). The low energy levels of the substrates introduced, and the high biomass wash-out rates both, appear to favour MPB at the expense of SRB.

Anaerobic digestion is assumed to be more sensitive to toxicants than its aerobic counterpart. Though not a misconception, this assumption currently requires re-evaluation. Three main factors determine the capacity of a biological treatment system to cope with toxic and recalcitrant chemicals: the nature of the chemical conversions; the ecophysiology of the microorganisms involved; and process design and plant operation.

Anaerobic treatment systems for municipal wastewater

If anaerobic processes could be shown to treat dilute wastewater consistently and reliably, it would be a highly significant development in wastewater treatment. Since anaerobic fermentation results in a lower cellular yield, less sludge is generated, and hence lower sludge handling costs would be possible. In addition, lower energy requirements would result, since aeration would not be necessary, and methane would be produced as a byproduct. In fact, the treatment of wastewater might be a net energy producer (Switzenbaum 1984).

Originally, anaerobic treatment was the preferred process for domestic wastewater management. Imhoff modified the septic tank for wastewater treatment in Germany, and by 1933 the Imhoff tank was used by over 240 towns in Germany. In general, these early processes were poor for removal of soluble BOD but were successful in capturing solids. Thus the anaerobic processes were abandoned, in practice, for liquid municipal wastewater treatment, with the development of stricter effluent standards and, until the middle part of the 1970s, the anaerobic fermentation process was not considered practical for treating low strength wastewater (BOD<500 1000 mg/l).

Beginning in the middle part of the 1970s, several studies of domestic wastewater treatments with the new generation of anaerobic reactors (the anaerobic fluidized bed, anaerobic filter, and upflow anaerobic sludge blanket processes) were published. These studies will be described in the remaining parts of this section.

Anaerobic filter studies

There have been numerous reports on the development of the ANFLOW process, an anaerobic filter type process, from lab to pilot demonstration scale (Genung 1980; 1987). At hydraulic retention times of 9 - 10 hours and a loading rate of 0.25 kg/m^3 /day for both TSS and BOD, 80% TSS removal and 70% BOD removal were achieved. This degree of efficiency was maintained in cold weather (=12°C water temperature) but the rate of solids accumulation in the reactor was higher, and methane production decreased. The primary mechanism for the initial removal of TSS (and consequently much of the BOD) appeared to be biophysical filtration, thereby explaining why removal efficiency was not affected by temperature. The concentration of entrapped solids increased continually throughout the study period, and Genung noted that a management plan to remove such solids periodically was necessary. There have been other lab scale evaluations of the anaerobic filter for domestic wastewater treatment with similar findings.

Anaerobic extended and fluidized beds

Hickey and Switzenbaum (1988) reported on the development of the anaerobic expanded bed process, which was found to convert dilute organic wastes to methane at low temperatures and at high organic and hydraulic loading rates. This process was being evaluated in 1988, on a 10,000 gallons per day pilot scale, consisting of an anaerobic expanded bed followed by post- treatment. Jeris (1987) reported on a two year experiment, testing two pilot scale anaerobic fluidized bed reactors, treating primary effluent. One reactor used sand as a carrier, the other granular activated carbon (GAC). Seeding experiments indicated that the GAC developed a biofilm more quickly and had more attached biomass. In addition, better BOD removal was observed with the GAC reactor. He noted that removal efficiencies were essentially independent of organic volumetric loading rates. Over a twelve month period in temperate climates, effluent total BOD_5 values were consistently around 40 mg/l.

Research continues on the use of fluidized bed reactors for sewage treatment in Japan, in the "Biofocus - WT" project, which is organized by the Ministry of Construction. It is proposed that the high organic removal efficiency of the process can be attributed to its ability to detain and degrade particulate organics. Best performance was also obtained with GAC in both the bench and pilot scale reactors by Brown et al. (1985).

UASB studies

The upflow anaerobic sludge blanket process (UASB) is by far the most widely studied reactor configuration for domestic wastewater treatment. Its primary use is for the treatment of higher strength industrial wastewaters, but it can be used for lower strength municipal wastewater - especially in tropical areas (Lettinga et al. 1984). At temperatures exceeding 12°C, COD removal efficiency was around 60% and was not greatly influenced by temperature, loading rates, or HRT. However, at temperatures below 12°C, removal efficiency was significantly lowered. In later studies (using granular sludge as seed material), it was concluded that conventional UASB technology was not attractive for treating very dilute and very septic sewage under cold climate conditions (de Man et al. 1988). The authors noted the importance of good feed inlet construction for obtaining better contact between the immobilized organisms and the influent wastewater. Better contact of organisms and wastewater can be achieved by a) greater height/diameter ratio, and b) recirculation of the effluent, which results in an expanded granular sludge bed (EGSB). The EGSB reactors had better contact and showed improved removals of soluble pollutants, making the EGSB look more attractive for treating cold and low strength wastewaters, after primary settling. The lower upward liquid velocities in the UASB reactors resulted in better entrapment of the non-soluble pollutants. Thus it is possible to improve UASB performance by increasing the contact between the wastewater and the organisms.

Because of these temperature effects, the UASB process has been more frequently applied to tropical areas where wastewater temperatures are usually at least 20°C. Savelli-Gomes (1985) reported on efforts by the sanitation company of the state of Parana, Brazil in treating domestic wastes anaerobically, mainly for the production of biogas. Over 20 plants for small communities have been constructed, with various combinations of anaerobic processes: septic tanks, anaerobic filters, Imhoff tanks, and UASB reactors. Three conventional UASB reactors have been constructed (small full scale) for the treatment of domestic wastewater. At Pirai do Sul, domestic sewage, along with the municipal solid wastes, industrial and agricultural wastes were treated in a full scale UASB reactor system, which supplies biogas to 286 homes. The system was operating well and achieving good quality effluent.

In Sao Paulo, Brazil a major effort is being made to develop anaerobic sewage treatment systems. Vieira (1988) reported

on studies being conducted by Companhia de Tecnologia de Saneamento Ambiental. Originally, experiments were conducted with 106 l capacity UASB reactors. Encouraging results were obtained at average HRT of 4 hours and ambient temperatures (winter 20° and summer 22°C). Effluent values of 57 mg BOD/l, 155 mg COD/l and 59 mg SS/l were obtained with variations in hydraulic loading, organic 3 loading and temperature. Later experiments with a 120 m^3 UASB reactor confirmed these results (at HRT of 6.5 hours, effluents of 113 mg COD/l and 48 mg BOD/l were obtained; at HRT of 4.7 hours effluents of 132 mg COD/l and 59 mg BOD/l were obtained, with SS of 45 mg SS/l). Based on the success of this demonstration, numerous full scale UASB reactors are being planned in Brazil.

Other demonstration scale UASB react ors are being planned or constructed in Pereira, in Bucaramanga by the Dutch consulting firm DHV, and in Bogota, Columbia (Orozco 1987). Further evaluation is currently being done in Ghent, Belgium, in Bologna, Italy (De Poli 1989) and in Kanpur, India. Zhao and Wu (1988) noted the development of anaerobic technology in China to treat concentrated human excrement and for on-site clusters. Of particular significance are efforts being conducted in Japan by the Aqua Renaissance '90 associates, which was organized by the Japanese Ministry of International Trade and Industry (1988). Wastewater is first concentrated by a membrane process, then treated by a UASB process. Table 7.1 lists present demonstration and pilot activities involving anaerobic sewage treatment (Switzenbaum 1988). As can be seen, UASB technology is most used in tropical areas (where the wastewater is warm). A notable exception is the Aqua Renaissance '90 project in Japan where the wastewater is first concentrated to overcome the problems with dilute wastewater treatment. In addition, the project in Bogota, Valladolid, Ghent, Japan, and New York must deal with cold sewage (below 12°C).

Conclusions

1. Aerobic microbial communities have several specific advantages. They have large free energy potentials, enabling a variety of often parallel biochemical mechanisms to be operated. These communities are therefore capable of coping with low substrate levels, variable environmental conditions and multitudes of different chemicals in the influent.

They have some very useful capabilities such as nitrification, denitrification, phosphate accumulation, ligninase radical oxidation, etc. which make them indispensable in waste treatment.

2. Anaerobic microbial communities are specifically advantageous at high temperatures and high concentrations, of soluble, but particularly of insoluble, organic matter. They also have special physiological traits, such as reductive dechlorination.

3. In the near future, important progress can be expected with regard to the optimal linkage between anaerobic and aerobic processes. Aerobic treatment needs to be specifically focused on the removal of the soluble pollutants.

4. Both in aerobic and anaerobic treatment there is an urgent need for better control and regulation. Particularly on- line monitoring of the biologically removable load (BOD, NOD) and of the possible presence of toxicants is necessary, to improve both types of processes as well as their combined application.

5. It is evident that a long solids residence time (SRT) is necessary for the treatment of sewage by anaerobic processes, because of the low specific growth rates associated with anaerobic bacteria.

6. Fixed-film microbial growth provides intimate contact between the various anaerobic bacteria, thereby providing rates of reaction and degrees of stability which cannot be obtained in suspended growth systems.

7. Up to 1988, either the expanded (or fluidized) bed reactor or the UASB reactor appeared to offer the most desirable configurations for anaerobic sewage treatment. Expanded or fluidized beds have the advantage of hydrodynamic control of film thickness and density, factors which allow them to achieve extremely high biomass concentrations; however, they are more mechanically complicated. They can be improved to a certain degree by increasing the recirculation rate (such as the EGSB).

8. Control of film thickness and density is not currently possible in the anaerobic filter. This places a relatively high lower limit on the HRT that can be utilized, and can eventually lead to process failure by plugging. In general, however, there is a need for more information on the influence of various engineering variables on film density and thickness, especially hydrodynamic factors.

9. In general, the UASB reactor did not use primary treatment, while anaerobic expanded or fluidized bed reactors did. The reason for this lies in the mechanisms of particle entrapment and hydrolysis in the two systems.

10. If secondary treatment is required, the prevention of solids inventory and handling problems, due to the buildup of inert solids in a reactor with long SRT and short HRT would dictate the need for primary treatment. If secondary treatment is not required, one could use a shorter SRT to achieve the required treatment objectives, and both solids reduction and soluble organics removal could be accomplished in the same reactor.

11. The fate of various wastewater fractions in an anaerobic reactor must be examined, to determine what are the constituents which make up the influent and effluents from these reactors, and whether some pass through untreated. Much of the data in the literature shows that removal efficiencies for sewage have little correlation with organic volumetric loading rate, suggesting that certain constituents in sewage have such low degradation rates, anaerobically, that they are only slightly removed, even under the lowest loading conditions. If these constituents are aerobically degradable, then the effluent from even a "perfect" anaerobic reactor may require further polishing before discharge to a stream, requiring secondary treatment.

12. Another open question is the impact of temperature on the kinetics of biodegradation of various fractions. At low temperatures there may be some materials whose rate of degradation is so low that appreciable removal could not be achieved even at a very long SRT. If that is the case, then anaerobic sewage treatment may be economically feasible only in warmer climates.

13. A better understanding is also needed of the distinction between the destruction and conversion of organic matter, and the coagulation and removal of particulate organic matter. The use of solids filtration in conjunction with an anaerobic reactor might be a useful combination.

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Chapter seven: Anaerobic processes, plant design and control

Digester types
Sizing of digesters
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Control device in an anaerobic digestion process
Process control

Digester types

Carrying out anaerobic digestion in a closed reactor, with sufficient volume for the biological reactions to occur without stress, comprises the primary technical requirement. Based on external limitations, such as capital outlay, treatment efficiency, net energy yields and operational skill, the technology available ranges from very rudimentary to quite sophisticated systems for both family scale and full commercial scale. The fact that anaerobic digestion has been used in practical situations for over 100 years demonstrates that it is a viable technology. Problems can arise, however, when there are external constraints, such as limited capital and low operational skills.

Many biogas officers in Developing Countries and commercial companies in Developed Countries have the optimum technology to tailor a plant to specific situation. The following is a summary of the main types of digester in common use.

Batch and Dry Fermentation: This is the simplest of all the processes. The operation involves merely charging an airtight reactor with the substrate, a seed inoculum, and in some cases a chemical (regularly a base) to maintain almost neutral pH. The reactor is then sealed, and fermentation is allowed to proceed for 30 - 180 days, depending on ambient temperature. During this period, the daily gas production builds up to a maximum, and then declines. This fermentation can be conducted at "normal" solids content (6 - 10%) or at high concentrations (>20%), which is then known as "dry" fermentation. Its main components are shown in Figure 7.1.

Figure 7.1: Batch Digester.

One of the most successful biogas programs using batch systems has been that of Maya Farms in the Philippines (Maramba 1978). Using a 1:1 dilution of swine manure (12.5% total solids, 10.0% volatile) and a residence time of 30 days at around 30°C, average volumetric efficiencies of around 1.0 0% were obtained. This was achieved with a seed inoculum of 20% by weight of the total digester slurry, which resulted in maximum gas production rates. By using more than 30 reactors extensively, emptying and recharging one each day, a

constant supply of biogas is ensured.

As evident from the description of anaerobic digestion up to now, the "Batch" system is inefficient, but cheap to build.

Considerable interest has been shown in "dry" fermentation, a process which Jewell et al. (1981) have worked on for a number of years. They found that fermentation can proceed at total solids concentrations up to 32%. With a . of grass mixed with manure at 25% total solids and 35°C, using a manure inoculum of 30% by weight, they obtained volumetric gas productions of 0.79 l\l\d over 60 days, which increased to around 3.0 l\l\d at 55°C. They concluded that such a reactor would have to be started only once a year. The unloading and use of the digested slurry can therefore be planned in advance.

The stage of development of "dry" fermentation and the process parameters need further work and research. However, even at this stage it appears to be a viable technology, and its gas production rates are competitive with semi-continuously fed reactors.

Fixed Dome (Chinese): A fixed dome biogas digester was built in Jiangsu, China as early as 1936, and since then considerable research has been carried out in China on various digester models. The water pressure digester was developed in the 1950s. In one variation, the displaced effluent flows on to the roof of the reactor, enabling the roof to withstand the gas pressure within more easily.

In terms of absolute numbers, the fixed dome is by far the most common digester type in Developing Countries. This reactor consists of a gas-tight chamber constructed of bricks, stone or poured concrete. Both the top and bottom of the reactor are hemispherical, and are joined together by straight sides. Some new structural Considerations have been published lately (Tentscher 1989). The inside surface is sealed by many thin layers of mortar to make it gas tight, although in the old type digesters gas leakage through the dome was often a major problem. This was changed in the new Chinese type of design. The digester is fed semi-continuously (i.e. once a day), the inlet pipe is straight and ends at mid-level in the digester. There is a manhole plug at the top of the digester to facilitate entrance for cleaning, and the gas outlet pipe exits from the manhole cover.

The gas produced during digestion is stored under the dome and displaces some of the digester contents into the effluent chamber, leading to gas pressures in the dome of between 1 and 1.5 m of water. This creates quite high structural forces and is the reason that the reactor has a hemispherical top and bottom.

At present there are about 5 million family-sized fixed dome plants of 6, 8 and 10 m^3 digester volume operating in China, and the target is 400,000 to 500,000 of the small size household digesters and 25,000 for medium and large scale (farms, distilleries, etc.) annually. Although China has the largest construction activity of all countries in the region, it is slow in relation to the huge potential. The new attitude is to develop positively, pay attention to both construction and to management, and seek for practical benefits. Sound work and quality in construction are being emphasized. Construction of family sized fixed dome digesters is well advanced and already standardized at national level. Solid experience is available with regard to the properties of construction materials, technique and design. This is outlined in training material. Construction material and technique is selected at the site (e.g. brickwork, lime-mortar, cement-mortar, concrete cast-in-place, etc.) to keep costs low. A brick dome may be constructed on an umbrella-shaped framework or a concrete cast-in-place digester used.

The design of fixed-dome digesters has been developed in China in respect of (a) the four important horizontal lines; (b) gas pressure; (c) average rate of gas production; (d) gas storage; (e) digester size; (f) geometric forms, loads and forces. The inside water level at ambient pressure is at 95% of total volume. The gas pressure in fixed-dome digesters is equal to, or below, 120 cm of water. Ratios of key dimensions are kept constant, e.g. diameter to height of the cylinder is 2:1. The HRT, for both cow and pig manure, is 35 - 40 days at total solids concentrations of 5 8% an] 4 - 7%, respectively. Gas production varies between 0.15 0.6 m per day, depending on ambient temperature. The state of development of fixed dome digesters is quite advanced and much is known about material, methods of construction, cost, suitable digester feedstock and gas production rates.

Figure 7.2: Fixed Dome (Chinese) Digester

Floating Dome (Indian or KVIC Design): In India, the history of biogas technology has developed since 1937. In 1950, Patel designed a plant with a floating gas holder which caused renewed interest in biogas in India. The Khadi and Village Industries Commission (KVIC) of Bombay began using the Patel model biogas plant in a planned program in 1962, and since then it has made a number of improvements in the design.

The Floating Dome digester is disseminated by KVIC and workshops recognized by KVIC. Those most commonly constructed are of 6 and 8 m^3 gas production capacity. The digester is designed for 30, 40 and 55 days' retention time: the lowest time applies to the hot southern States, the highest to the cooler northern States. Construction costs vary according to ambient temperatures, for which partial compensation is allowed for by subsidies. The main material fed is cattle manure. At community plant level, nightsoil is digested in a mixture with cattle dung, and at large farm level other types are being introduced, to digest materials such as water hyacinth. The drum was originally made of mild steel, until fiberglass reinforced plastic (FRP) was introduced successfully, to overcome the problem of corrosion. Nearly all new digesters are equipped with FRP gas-holders.

The cost of a mild steel gas-holder is approximately 40 50% of the total cost of the plant. FRP gas-holders are 5 - 10% more expensive than the steel drum. The following Table gives the cost of FRP drums in two different enterprises visited.

Table 7.1. Comparison of Cost of FRP Gas-holders

For Digester of m^3 gas/day	KVIC turnkey worker near Bombay		Industrial Enterprise near Coimbatore	
	Weight (kg)	Cost (Rs)	Weight (Kg)	Cost (Rs)
3	-	3,200	48	4,000
4	-	3,400	-	-
6	-	4,200	70	5,800
8	-	5,200	85	7,150
10	-	-	193	10,500

No. of fiberglass layers	2		3
From Tentschner (1989).			

The daily production capacity of FRP drums by a KVIC turnkey worker near Bombay was higher than steel drum production capability: 3 FRP drums can be made in 5 work days, while 2 steel drums require 8 work days. The floating dome design, upon which the KVIC model is based, is used extensively throughout the world. A typical KVIC design is shown schematically in Figure 7.3. The reactor wall and bottom are usually constructed of brick, though reinforced concrete is sometimes used. The gas produced in the digester is trapped under a floating cover, which rises and falls on a central guide. The volume of the gas cover is approximately 50% of the total daily gas production. The pressure of the gas available depends on the weight of the gas holder per unit area, and usually varies between 4 - 8 cm of water pressure.

Figure 7.3: Floating Dome (Indian) Digester

The reactor is fed semi-continuously through an inlet pipe, and displaces an equal amount of slurry through an outlet pipe. When the reactor has a high height: diameter ratio, a central baffle is included to prevent short circuiting.

Most of the KVIC type digesters are operated at ambient temperatures, so that retention times depend on local variations. Typical retention times are 30 - 40 days in warm climates, such as Southern India, where ambient temperatures vary from 20° - 40°C, 40 - 50 days in moderate climates, such as the Central and Plains areas of India, where minimum temperatures go down to 5°C, and 50 - 80 days in cold climates, such as the hilly areas of Northern India, where minimum temperatures go below 0°C.

Typical feedstock is cattle dung, although substrates such as agricultural residues, nightsoil and aquatic plants have been used. Cattle manure, generally about 20% solids, is diluted to 10% total solids before feeding, by adding an equal quantity of water. The daily average gas yield varies from 0.20 to 0.60 volume of gas per volume of digester ratio in cold to warm climates.

Many laboratories, universities, and industries throughout the world, and especially in India, continue to improve the KVIC design. Efforts are being made to optimize the design parameters, to improve the volumetric efficiency, and make the facilities economically and structurally sounder. Heating, mixing and insulation have been introduced on an experimental basis, as well as modifications in geometric configurations and locations of inlets and outlets.

Janata Model. This type of digester is disseminated by the Indian NGO network of AFPRO and many government agencies. It is 20 - 30% cheaper than the floating drum model, and uses local materials to a much greater extent. It has the limitation that only good quality materials and expert construction produce a satisfactory plant.

Nearly all sizes of Janata digesters are designed for 60 days' retention time. This is a clear disadvantage compared to the KVIC type. A standardization of three different retention times has yet to be approved by DNES. A wide range of sizes, from 2 - 30 m^3 daily gas production are made; the most common sizes are 2, 3, 4 and 6 m^3 gas/day. Discussions are being held to change and improve the design of the Janata model.

Table 7.2: Janata Model: Loading and Production Characteristics.

Gas prod-uction (m /day)	Daily fresh dung (Kg)	Volume of dig-estion chamber (m^3)	Gas prod-uction (m^3 /m^3 /day)
2	50	6.0	0.34
3	75	9.5	0.33
4	100	12.0	0.33
6	150	18.5	0.32

Source: Khandelwal and Mahdi (1986)

Up to 1986, a total to 642,900 digesters had been built in India. Community and Institutional Biogas Plants (IBP) are also being constructed. Poor farmers and low castes are supposed to be involved and to participate in operation of Community Plants (CBP).

Table 7.3: Total Number of Digesters Constructed in 1985/6 at Family Level and Approximate Share of Executing Agencies.

Agency	Number	%	Type
KVIC	20,000	10.8	Floating drum
Governmental	156,000	84.4	mainly Janata
AFPRO/NGO	9,000	4.8	Janata
Total	185,800	100.0	

Table 7.4: Installation of Family-Sized Biogas Plants by KVIC

Period	No. per Period	Cumulative Total
Up to March 1975	13,508	13,508
During Vth Plan	65,905	80,113
1980/81	7,964	88,077
1981/82	9,180	97,257
1982/83	11,033	108,290
1983/84	15,029	123, 319
1984/5	18,224	141,543

1985/86 (target)	20,000	161,543

Source: KVIC (1984)

Table 7.5: Completed Community and Institutional Biogas Plants up to End 1985

Period	Up to 31.3.85.		During 1985/86		Total
Digester type	CBP	IBP	CBP	IBP	
Number	48	53	24	9	134

Source: Annual Report 1985/86. DNES, Ministry of Energy.

Bag Design (Taiwan. China): The bag digester is essentially a long cylinder (length: diameter 3:14) made of PVC, a Neoprene coated nylon fabric, or "red mud plastic" (RMP), a proprietary PVC, to which wastes from aluminum production are reported to be added. Integral with the bag are feed and outlet pipes and a gas pipe (see Figure 7.4). The feed pipe is arranged so that a maximum water pressure of approximately 40 cm is maintained in the bag. The digester acts essentially as a plug flow (unmixed) reactor, although it can be stored in a separate gas bag (Park et al. 1979).

[Figure 7.4: Bag-Red Mud (Taiwan, China) Digester.](#)

The basic design originated in Taiwan, China, in the 1960s (Hao et al. 1980), due to problems experienced with brick and metal digesters. The original material used, a Neoprene coated nylon, was expensive and did not weather well. In 1974 a new membrane, RMP, was produced from the residue from aluminum refineries. It was inexpensive and has a life expectancy of up to 20 years (Hong et al. 1979). Due to its availability, PVC is also starting to be used extensively, especially in Central America (Umana 1982). The membrane digester is extremely light (e.g. a 50 m^3 digester weighs 270 kg), and can be installed easily by excavating a shallow trench, slightly deeper than the radius of the digester. Due to its simple construction, and the fact that it is prefabricated, the cost of this digester is low, around $30 per m^3.

The Taiwanese evolved the bag digester primarily to treat swine manure, which is also the most common substrate in Korea and Fiji. Due to its low cost and excellent durability, the Chinese have also started producing these digesters, and claim that the cost is as low as $25 to $30 per m^3. Depending on the availability of the plastic, a rapid expansion in the use of bag digesters is expected in China, and in time it may replace the fixed dome as the preferred type in China.

Typical retention times in bag digesters, for swine waste, vary from 60 days at 15° - 20°C, to 20 days at 30° - 35°C. One advantage of the bag is that its walls are thin, so the digester contents can be heated easily if an external heat source, such as the sun, is available. The Chinese have found that average temperatures in bag digesters, compared with dome types, are 2° - 7°C higher. Hence specific yields can be from 50 - 300% higher in the bag (0.235 - 0.61 volumes of gas per volume of digester per day). Park et al. (1979) also found this to be true in Korea, and obtained specific yields varying from 0.14 in winter (8°C) to 0.7 in summer (32°C) for swine manure.

In their present state of development, bag digesters appear to be very competitive, because of their low cost. However, more data are needed on their durability, with regard to weather and mechanical failure (e.g., sharp objects piercing the bag). The potential for increasing their performance by heating with solar tents should also be explored.

The RMP or semi-plastic digesters in China are commonly batch type dig esters. They are filled with straw and manure and operated for 6 - 8 months. Discharging is easy because the RMP gas-holder can simply be removed. Even when cracks in the wall occur, it does not affect gas production. The film is fixed with bricks in a water jacket and seals the digester completely. The RMP material is also used as a gas barrier, for pipes and hoses and for many other applications outside the biogas sector. At present there are about 50,000 RMP digesters of over 10 m^3 operating in China.

Plug Flow Design: The plug flow reactor, while similar to the bag reactor, is constructed of different materials and classified separately. A typical plug flow reactor consists of a trench lined with either concrete or an impermeable membrane (see Figure 4.5). To ensure true plug flow conditions, the length has to be considerably greater than the width and depth. The reactor is covered with either a flexible cover gas holder, anchored to the ground, or with a concrete or galvanized iron top. In the latter type, a gas storage vessel is required. The inlet and outlet to the reactor are at opposite ends, and feeding is carried out "emi-continuously, with the feed displacing an equal amount of effluent at the other end.

[Figure 7.5: Plug Flow Digester.](#)

The first documented use of this type of reactor was in South Africa in 1957 (Fry 1975), where it was insulated and heated to 35°C. Specific yields (vol. gas/volt digester/day) of 1 - 1.5 were obtained, with retention times of 40 days and loading rates of 3.4 kg total solids per m / day.

Jewell and his colleagues at Cornell University have carried out a considerable amount of work on this design over the last 8 years. Hayes et al. (1979) described a comparison between a rubber lined plug flow reactor and a completely mixed digester. Both had a total volume of 38 m , and were fed on dairy manure at 12.9% total solids. Their results are summarized in Table 7.6. Digester temperatures were not stated, but it is assumed that both were maintained at 35°C.

Table 7.6: Comparison of Completely Mixed Digester with Plug Flow Digester

	Completely	Mixed	Plug	Flow
HRT (d)	15	30	15	30
Specific volume (m$_3$ gas/m^3 reactor/days)	2.13	1.13	2.32	1.26
Specific gas production (m^3 /kg VS Added)	0.281	0.310	0.337	0.364
Gas composition (%CH$_4$)	55	58	55	57
Volatile solids reduction (%)	27.8	31.7	34.1	40.6

Reference: Hayes et al. (1979).					

The plug flow reactor gave higher gas production rates than the completely mixed one. The high specific yield, compared with figures for typical fixed dome and floating dome designs, of 0.1 0.3, are due to higher temperature and higher loading rates. At 20°C the plug flow reactor yields about 0.42 volumes of gas per volume of digester per day. At typical lower loading rates (9% versus 12.9% total solids) this figure would decrease to around 0.29.

Anaerobic Filter: Apart from the batch digester, all the designs discussed above are known as suspended growth systems, and when there is no recycling of solids, the hydraulic retention time (HRT) is equal to the biological solids retention time (ϕ). Due to the slow growth of anaerobic organisms, ϕ has to be of the order of 20 - 60 days, depending on the temperature, in order to prevent the active organisms from being washed out, and process failure occurring. HRT is also high, and reactor volumes are substantial, leading to specific yields.

In order to reduce reactor volume, a unit known as the immobilized growth digester has been evolved. One of the earliest and simplest types of this design was the anaerobic filter. This typically consists of a tall reactor (H/D = 8 - 10) filled with media on, or in which the organisms can grow or become entrapped (see Figure 7.6). Media used have varied from river pebbles (void volume = 0.5) to plastic media (0.9), although any material which provides a high surface area per unit volume is suitable. The choice of media depends on considerations such as cost, void volume, availability and weight. The waste to be treated is usually passed upward through the filter, and exits through a gas syphon, although downflow configurations can be used. The organisms growing in the filter consist of two types: those attached to the media, and those entrapped in a suspended form, within the interstices of the media. At low hydraulic loading rates, both sorts are prevalent, while at high hydraulic loads the suspended organisms are washed out, leaving only the attached forms. Due to entrapment and attachment, high biological solids retention times (ϕ) are possible, at very low HRTs.

Additional information is presented in Chapter 6, concerning wastewater treatment by anaerobic filter systems.

Figure 7.6: Anaerobic Filter.

Because of the physical configuration of the filter, only soluble wastes can be treated without blockage, although diluted pig waste has been treated successfully, with a total solids content of 2% (Chavadej, 1980). Waste strengths from 480 ppm COD up to 90,000 ppm COD have been treated in filters, and retention times as low as 9 hours, based on void volume, are possible with COD removal of 80% (Young and McCarty 1969). However, more typical retention times are in the order of 1 -2 days (Arora and Chattopadhya, 1980), and at these times over 90% COD removals are possible. Loading rates as high as 7 kg COD per m /day are possible, and under these conditions specific yields of 4.0 have been measured (Xinsheng et al. 1980).

Anaerobic Baffled Reactor: This design, which is very recent, was evolved by Bachmann et al. (1982) at Stanford University. The reactor is a simple rectangular tank, with physical dimensions similar to a septic tank, and is divided into five or six equal compartments, by means of partitions from the roof and bottom of the tank (see Figure 4.7). The liquid flow is alternately upward and downward between the partitions, and on its upward passage the waste flows through an anaerobic sludge blanket, of which there are five or six. Hence the waste is in intimate contact with active biomass, but due to the design, most of the biomass is retained in the reactor.

With a soluble waste containing 7.1 g/l COD and a retention time of 1 day at 35°C, Bachmann et al. (1982) obtained 80% removal efficiencies of COD, with a specific yield of 2.9. Similar tests have been carried out with diluted wastes (0.48 g/l COD) and similar performance we. obtained at 25°C. Due to its physical configuration, this type of reactor appears to be able to treat wastes with quite high solids contents, and hence may be an alternative to anaerobic filters. Since the process is new, little developmental work has been done on it, but it could be applicable in Develanina countries under certain circumstances.

Figure 7.7: Anaerobic Baffled Reactor (ABR).

Additional information is presented in Chapter 6 concerning wastewater treatment by anaerobic filter system.

Anaerobic Contact Process: This process in similar to the aerobic activated sludge process, in that cell recycling is used to maintain high (ϕ) at low HRT. Hence, good removal efficiencies can be obtained with small reactors. Since the anaerobic sludge is still actively producing gas when it exits from the digester, problems have been experienced in getting it to settle quickly. Various methods have been used to get around this problem, including thermal shock and vacuum degasification (see Figure 7.8).

The first recorded instance of use of the anaerobic contact process occurred in 1955 (Schroepfer et al. 1955) where waste from a meat packing house (BOD 1.6 g/l) was treated successfully at retention times of only 12 hours at 35°C. BOD removals of 95% were obtained, at loading rates of 3.2 kg BOD per m^3/day and, even at 25°C, removals of 95% were achieved. Many food wastes can be treated efficiently using this process. With rum stillage (COD 54.6 g/l) removals of 80% were obtained, at loading rates as high as 8.0 kg COD per m^3/day (Roth and Lentz 1977). Raw sewage (COD 1.2 g/l) has been treated at 20°C, with low retention times (22 hours) in a contact process, and high removals (90%) were obtained (Simpson 1971).

While some full scale plants are currently operating in Developed Countries, there are no known plants in Developing Countries. With high- strength industrial wastes, it would appear that other anaerobic processes (e. g., filter, ABR) would be just as efficient, easier to operate, and require less capital outlay.

Figure 7.8: Anaerobic Contact Digester

Upflow Anaerobic Sludge Blanket (UASB): This process is quite recent, and was developed by Lettinga et al. (1979, 1980) in the Netherlands. The reactor consists of a circular tank (H/D = 2) in which the waste flows upward through an anaerobic sludge blanket comprising about half the volume of the reactor (see Figure 4.9). An inverted cone settler at the top of the digester allows efficient solid-liquid separation. During start-up, the biological solids settle poorly, but with time a granular sludge develops that settles extremely well, and the active biomass is retained within the reactor.

With predominantly soluble industrial wastes 3 (potato processing wastewater) loading rates as high as 40 kg/m /day COD are possible, with retention times as low as 3.5 hours. Under these conditions volumetric gas production figures of 8.0 are possible (Lettinga et al., 1980). Since the process does not use media to maintain the active biomass, total solids content in the feed can be as high as 3%. Operation requires a relatively high degree of sophistication, especially during the critical start up phase. In most cases, alternative designs (filter, ABR) are available with a lower degree of complexity.

Inclined Tubular digesters: The effects of aspect ratio, digester inclination to the horizontal and retention time were investigated (Chapman et al. 1988) and its performance on laboratory scale investigated (Floyd and Hawkes 1986). The digester is a modified form of the horizontal displacement digester: the digestion vessel is tubular, but inclined at an acute angle to the horizontal. Thus, the main advantages of a horizontal displacement digester are retained, while the exposed surface area of the digester contents, where scum and crusts can form, is minimized. It is also mechanically simpler to remove any scum and crust which does form. Operation of the digesters was reliable, and there were no recurring problems. Gas yields ranged from 0.282 - 0.318 m /kg VS added, with whole slurry at 35°C. The greater gas yields from the inclined tubular digesters are attributed to longer retention of particulate material within the digester than in CSTR systems. The main applications of this design are likely to be for treating particulate waste" of <8% TS concentration, where some settling will occur.

[Figure 7.9 Upflow Anaerobic Sludge Blanket (UASB).](#)

Sizing of digesters

As discussed in Chapter 4, anaerobic digestion depends on the biological activity of relatively slowly reproducing methanogenic bacteria. These must be given sufficient time to reproduce, so that they can replace cells lost with the effluent sludge, and adjust their population size to follow fluctuations in organic loading and the generation of volatile acids and other substrates from the earlier steps. If the rate of bacteria lost from the digester with the effluent slurry exceeds the methanogen growth rate, the bacterial population in the digester will be Uwashed out" of the system. Washout is avoided by maintaining a sufficient residence time for solids, and thus bacterial cells remain in optimal concentration within the digester.

Designing a properly sized digester to obtain the maximum biogas production per unit of reactor volume is important in maintaining low capital construction costs. The digester should be sized to achieve desired performance goals in both winter and summer, and must be large enough to avoid "washout."

Design goals could be maximal gas production with minimal capital investment, achieving pollution control and reduction of pathogens, or simply the production of a reasonable amount of gas with a minimum of operational attention. The uses of the slurry after the digestion process is a critical consideration since the main income to the plant can come from that material. The differences in uses also determine the digestion retention time. Criteria must be established, prior to design, since not all goals can necessarily be achieved with a single design. Assuming that adequate performance data are available for the feedstock under anticipated operating conditions, the digester can be designed for size and other features, such as the degree of heating and mixing, to meet the desired criteria.

Optimal methane production per m^3 digester capacity must allow a margin of safety in size, equal to several days' additional retention beyond "optimum", to ensure that occasionally stressful environmental conditions will not upset the maintenance of a viable methanogenic bacterial population. The extremely large safety factor used in conservatively designed sewage sludge digesters, to enhance pathogen destruction and pollution control of even toxic feedstock is not the most cost efficient for methane production. Desired results must therefore be determined prior to making sizing decisions.

A number of empirical methods have been employed in the design of conventional sewage sludge digesters, where emphasis has been pollution control and ecological reasons, rather than maximum biogas production. This situation has not been common in Developing Countries until recently, but in Indonesia, for instant, the anaerobic system that digests palm oil was designed and erected only because of ecological and legislative reasons. Conservative design parameters applicable to sewage sludge treatment also result in digester sizes of up to 50% larger than those needed for plants designed for maximum methane production. The ecological and environmental issues are receiving more importance in many countries, and will lead in the near future to different types of digesters.

Design of large installations, particularly those with a typical feedstocks, is based on a fundamental understanding of the anaerobic processes which achieve the desired performance goals. Large installations can also afford considerable attention to operation, allowing refinements in the process, such as control of temperatures, volatile acids and feedstock pumping, to improve biogas production rate per unit digester volume.

A major criterion for size in the design of anaerobic digesters is the mean cell (or solids) residence time (c) . The mean cell residence time is defined as the mass of bacterial cells in the digester divided by the mass of cells removed from the digester per day. For a conventional digester without solids recycle, is equivalent to the hydraulic retention time, (HRT), and is thus directly related to digester volume. It has been found that at a given temperature, most digester performance parameters of interest can be correlated with c, and that washout can be avoided if is maintained above a critical minimum value, c_m.

In industrialized countries, heating of digesters is common practice, and the trend has been toward thermophilic digestion, while in Developing Countries digesters are usually operated at ambient temperature". Because the anaerobic digestion process essentially stops at 10°C, the digester contents must be maintained at a temperature higher than this for significant gas production. Therefore design is based on critical temperature periods of the year, using anticipated temperature within the digester rather than ambient air temperature.

It is evident from Yeoh (1988) that utilization of biogas from the anaerobic treatment of palm oil brings about significant economic gains, which are particularly convincing in thermal conversion systems whose efficiencies have been reported to range from 0.7 - 0.9, compared with conversion efficiencies of 0.25 0.35 in electrical and mechanical systems. However, it is to be stressed that the assessment assumes high utilization of the biogas produced (80%), which may not be easily achievable at the present stage of development, considering the fact that the palm oil milling operation is largely self-sufficient, in terms of energy, through the use of fibre and shell; and therefore biogas produced from its effluent treatment plant represents an energy source mainly in excess of its own requirements. The economics of the anaerobic treatment system, as a revenue investment, therefore depends very much on the extent and the way that the biogas is used, particularly off-site.

Economic evaluation should be viewed only as a broad guide to the comparative cost-benefits of resource recovery from the anaerobic treatment of palm oil. Although it does provide a macro- view of the effects of digestion temperature and mode of biogas utilization on the bio-methanation system, through the translation from technical terms to tangible financial terms, the figures quoted should be taken as estimates. This is because important factors, such as operational variability and inflationary effects on costs and revenues were not considered. Furthermore, the benefits arising from biogas utilization are very sensitive to the actual value of the energy form for which it is substituted, which may vary considerably from case to case.

Anaerobic digesters can utilize a large number of organic materials as feedstocks. These include animal manures, human wastes, crop residues, food processing and other wastes, or mixtures of one or more of these residues and wastes. Animal manures exhibit good nutrient balances, are easily slurries and are relatively biodegradable. The range of biodegradability reported varies from 28 - 70%. This variation is partly due to the diet of the animals and amount of bedding to the animal that is also used digestion. For example, Hashimoto and Chen (1981) showed that as the percentage of silage is increased, at the expense of ground corn, the degradability of the manure decreases, since silage contains a high percentage of lignocellulose materials. Thus, in Developing Countries, where cattle are fed agricultural wastes, the manure is less biodegradable than where cattle are fed ground grains or commercial feed.

Fresh manure is much more biodegradable than aged and/or dried manure because of the substantial loss of volatile solids over time.

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Comparison of alternative design approaches

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Table 7.7 presents digester sizes calculated according to criteria for Indian (KVIC), USEPA (1979), Mullan et al. (1984), and this report. The 27°C temperature is based upon current Indian practice. Both the Indian and USEPA approaches result in larger and, from an operating stability standpoint, conservative sizes.

Table 7.7: Comparison of Calculated Digester Sizes Operating at 27°C Ambient Temperatures.

CASE	INDIAN (KVIC)[a]		WARD/SRRINDE[b]			USEPA (1979)[c]			SHAEFFER/MULLAN[f]		
	Size	HRT	CH4	Size	HRT	CH4	Size	HRT	Size	HRT3	CH4
	m^3	days	m^3	m^3	days	m^3	m^3	days	m^3	days	m^3
Fresh Manure											
10 cows[d]	40	50	3.6	3.6	10	3.6	40	100	6	15	3.6
Manure.											
Concrete Slab											
10 cows[d]	13	50	2.5	2.6	10	1.5	20	78	-	-	-
Manure and Dirt											
10 cows[d]	9	50	1.3	1.8	10	0.88	10	50	-	-	-
Pig Manure											
Fresh											
75 to 80 pigs[c]30	50	0.8	7.5	25	2.93	28	55		-	-	-

a) Based on ESCAP (1980) using 27°C;
b) Based on Hashimoto equations using 27°C;
c) Based on equivalent size assuming 80 g per capita per day solids from 90 people weighing 4,500 kg;
d) Assumes 4,500 kg total cattle weight (average 450 kg per animal;
e) Assumes 4,500 kg total live weight, manure collected fresh and flowing by gravity to a digester (no water added);
f) Mullan et al. 1984.

Problems and solutions of feedstocks and effluents in full-scale biogas plants (based on hobson, 1987)

Digester feedstocks
Mechanical problems
Chemical and biochemical treatments of feedstocks
Digester effluent

One of the main advantages of applied anaerobic digestion is that results from small scale experiments can be reproduced in a full-size plant. Thus, many aspects of the overall design (including the type: stirred-tank, UASB, etc.) and running of a digester system may be based on laboratory and pilot-plant experiments and scaled up. Some feedstocks used as

charging materials to the digestion system can be digested without problems while others can not. The solution of the problem of the resistance to digestion of a specific material may lie in further small-scale experiments, or it may mean modification and experimentation with the large-scale plant. The following section deals with the problems of feedstocks that are difficult to digest, and some solutions to this problem.

Digester feedstocks

The physical and chemical state of a material feedstock used for anaerobic digestion is initially determined by its source. The feedstock may be a clear liquid, a suspension of solids in a liquid, or a "solid" - a material with less than 70 - 80% water content. Various digester systems have been designed to treat these physically different forms of feedstock. Sometimes physical and chemical problems may be solved by modifying the feed. These modifications may allow the original type of digester to be used, or they may be such that a different type is needed.

Mechanical problems

Slurries Biodegrading of a feedstock material, to determine the feasibility of digestion of a particular waste, and the basic parameter" of biogas production, can usually be carried out on laboratory or small pilot plant scale. There may almost no problems in the use of wastewaters with dissolved substrates (except some very oily materials). However, mechanical problems in pumping and piping liquid wastes containing large suspended solids may dictate the minimum size of digester which can treat the raw waste. Obviously, chopping, maceration, or separation of large particles, to produce a suspension in liquid which can pass through small pipes, can profoundly alter the kinetics of solids digestion. Therefore, small-scale results with macerated solids may not be representative of large scale results with the raw feedstock. In small scale experiments, batches of feedstock for the digesters are usually collected from the main source. It is again obvious that these batches should be representative of the proposed large scale feedstock. Biodegradability experiments (Goering and Van Soest 1970; Jewell 1976; Kimchi 1984) were found to be a good tool for estimation of the extent a specific feedstock will be degraded.

Low solids wastewaters can be piped to digesters, as in any chemical process plant; high-solids sludges and slurries are different. Problems have become particularly apparent with cow- farm manures. Farm slurry systems are generally designed to move large volumes quickly. Most farm digesters are relatively small, and have long retention times. This means that small volumes of slurry have to be pumped and piped at low overall rates. The farm slurries contain grit, animal hairs and fibrous feed residues (straw) and these are incompatible with the use of the small bore pipes and pumps appropriate to the low slurry volumes fed daily to the digester. Pipes need to be 7.5 cm or more in diameter, as straight as possible, with any bends of large radius, and with full-bore valves, and must have provision for access to clean the line with a stick. Mono-type pumps are satisfactory (but rotors are amortized quickly), and their ability to run in reverse aids clearing of blockages (Hobson and Feilden 1982; Summers et al. 1984). They are suitable for feedstocks without stones or straw. The low daily flows required are obtained by intermittent pump operation for short periods. Similar pipe and pump systems are needed for the effluent of pumped outflow digesters, although much of the larger particulate material is disintegrated during digestion. Grit from animal house floors may not cause much problem with large-bore pipes, but it does increase the rate of wear of pumps, particularly centrifugal types. Larger stone" can cause blockage and breakage problems, as was found with some digesters taking feed from cattle feedlots with earth-floor enclosures (a good example is the large scale experiment in Oklahoma). Settlement, or coarse screening of the slurry may be needed in such cases. Settling of grit and other undigested materials occurs in the bottom of the digester, and reduces the available volume for digestion, thus reducing the HRT.

The published information on the engineering properties of farm wastes and slurry pumping and flow through pipes (e. g. Howard 1978; Chen 1982; Bohnhoff and Converse 1987) is relatively sparse, since companies keep such information as proprietary. Much of the building of farm digester piping has been done by trial and error, and the information is kept with the designers. This is to some extent unavoidable, as slurries that are nominally the same vary with animal feed and farm conditions, and there are large variations between pig, cattle and poultry waste slurries. Much also depend on

climate, temperature and local conditions.

The particulate solids in raw animal slurries (especially after drying in high outdoor temperatures) may either sink or float as the slurry stands in tanks (or pipes). Fibrous solids tend to form a "screen" and allow only the supernatant liquids to flow. Floating fibrous solids can dry out, to give a solid crust on slurries, which can be difficult to break up. This is especially true when low concentrations (4 - 6% solids) are used for digestion. Settled solids can block pipes and pumps that are taking slurry from the bottom of the tanks. After some time, settled solids can become very difficult to break up. Animal slurries have been mentioned, but solids settlement or flotation can occur in many industrial wastewaters, such as those containing starch granules, vegetable peels, yeasts from brewing, fragments of seeds from oil-extraction plant, slaughterhouse wastewater, etc. The problems can occur in pipes and channels or in feed tanks. Mixing of solids and liquid can sometimes be obtained by an intermittent rapid flow, as when sluices are opened to empty a slurry channel, or when slurry is circulated over the top of the tank. Pumps can be designed to recirculate liquid in a tank for some time, before switching to pumping the liquid out to another tank, or to a digester, or to macerate the materials for a short period before pumping. Paddle, Archimedean-screw or other mixers, or independent recirculation pumps may also be used. A number of macerators can be purchased cheaply from several companies. In the case of cotton stalks as with vegetable wastes, energy crops, fresh or ensiled, a stable sludge may be obtained by macerating the vegetation in water. Maceration may also prevent pipe and pump blockages by long-fibre vegetable material in animal excrete and other slurries. These methods attempt to keep the whole digester feedstock, or effluent in some cases, as a "homogeneous" suspension of solids. On the other hand it may in some cases be better to remove some, or all, of the solids. Slurries and sludges can be treated only in stirred-tank digesters; removal of suspended solids may allow the resulting liquid to be treated in some simpler digestion system. Some simple screens are used in cow barns to separate solids and fibres from the liquids and treat each of them differently. Settling tanks for grit are sometimes essential.

Solid Feedstocks. Because of the nature of the solid waste it may not be possible to use a continuous feed. In this case, batch digestion may be used. Batch digesters are of the single-stage, tank type or plug-flow, but may have either a liquid or a solid feedstock. Most batch digesters are designed for solid feeds, the type of digester being dictated by the above-mentioned difficulties of continuously feeding a solid substrate. The feed has to be mixed with an inoculum of the previously digested material, in order to start off the digestion process. Gas production then proceeds at an increasing and then decreasing rate, as the substrates are used up. To deal with a continuous supply of solid feed, and to produce a continuous supply of gas, a number of batch digesters must be run in rotation, one producing maximum gas, while others are in the starting-up or declining phases of gas production. This was very nicely shown in the MAYA farm in the Philippines.

Manures usually have a total solid (TS) content of about 8 16%. In most cases, especially when slurries are not "homogeneous", this concentration is too high for pumping and piping, and the TS is usually brought down to 6 - 8% by dilution with water, to make a pumpable slurry. Some vegetable matter (eg. seaweeds) may have such a high water content that the macerated material is of this order of TS, as well as pig manure and cow manure in "flashed system". However, some wastes are "solids" materials with more than 20% TS, and although containing water, are not pumpable. Examples of solid wastes are poultry excreta, with or without litter, and cattle excreta, with straw or other bedding. Many plant waste" and terrestrial plants grown as energy crops will give a digester feed of 25 - 30% TS. Unless this type of feedstock i" suspended in water and macerated, to produce a low- solids slurry it can be easily handled only in "solid-state" digesters (Jewell 1980). These are run batch-wise and are loaded and unloaded by grabs or tractor shovels which may feed the digester directly or indirectly. Even in this case, some chopping of large pieces of vegetation may be needed, but on the whole, solid-state digesters have few physical problems with either feed or effluent. The system is very similar to silage making but is rarely used for biogas production.

Digestion of solid materials has to be a continuous process, though the feedstock itself may be produced intermittently, as with some energy crops and crop residues, for instance. Continuous use of any digester, as with other chemical or power plants, is dictated by economic considerations of obtaining the best return on capital from the gas or other products of digestion (except in pollution control cases). Sometimes the digester will work only when the factory is operating. However, though the running of a digester may be intermittent, in the broader sense, running is as far as possible continuous during the period of use. Sayed et al. (1987) ran a UASB digester on slaughterhouse wastewaters. Feed was continuous during the week but stopped at weekends when the slaughterhouse was not in operation. Analysis showed that this weekend of pause in loading was beneficial, in that it allowed accumulated solids in the digester to be degraded to gas. Marchaim et al. (1991) found a similar situation in treating high solid concentration of slaughterhouse wastes.

Although a solid feedstock will not be pumpable in the usual sense, it may be possible to move it through pipes by conveyors. Thus, if a suitable digester can be designed, a continuous-flow digestion, similar to the stirred-tank for liquids, can be run. A typical digester is used for solid municipal refuse (de Baere et al. 1986).

Physical Pretreatment of Slurries and Solid Feedstocks Maceration of feeds has been mentioned above. With drier materials, such as straws, either alone or as constituents of a mixture (e.g. animal excrete and bedding), maceration reduces particle size to prevent physical obstruction of pipes and pumps by the fibres, and it also increases surface area available for microbial attack, and thus speeds up the digestion process. It was shown that lignin cellulose and hemi-cellulose which are almost non-biodegradable in ordinary systems can be degraded to an significant degree after maceration (Marchaim 1983). With fresher vegetable matter, such as seaweeds and water hyacinths, the cell walls of the algae or plants are only slowly degradable, and maceration frees soluble cell-contents, which provide the bulk of the digestible substrates, and also damages the cell walls to make them more susceptible to digestion. This type of feedstock should be relatively free of stones and other debris, or must be washed free of such material, so some type of rotary chopper can be used to reduce the particle size.

Municipal garbage and similar solids feeds may be mechanically, magnetically or hand-sorted, to remove large glass, metal and other non-biodegradable materials, and then macerated in an internally-toothed drum or other apparatus which will shred the waste, but will not be affected by stones or other hard debris. This type of shredder is not suitable for liquid slurries or slurries containing stones, lumps of wood, plastic sheets, etc. (eg. farm slurries) that may damage the choppers. This sort of operation is not dealt with in this review.

Separation of solids from farm slurries, particularly cattle wastes, has been advocated by many companies and farmers. Separation is done to remove the long plant fibres and cattle hairs, thus decreasing the possibility of pump and pipe blockages, and making a more homogeneous slurry. The large fibres removed are generally poorly biodegradable, and produce gas only at long retention times. The remaining particulate matter can be digested at short retention times, thus allowing the use of smaller digesters and lower capital costs. There will be some overall loss of gas production from a particular volume of original slurry, but this can be compensated for by the smaller digester and lower cost and more trouble-free pumping and mixing (Pain et al. 1984). The digested slurry obtained has a different structure and value than the "whole material" digested slurry. The solids removed could be digested in a long retention-time batch digester, but are more often aerobically composted, as they are relatively dry, stackable solids. Removal of most of the particulate matter by mechanical mean" or by gravity settlement can be performed. This leaves a wastewater of only 1 - 2% TS, most of which is dissolved. This waste can then be treated in a filter or UASB digester, at a relatively short HRT. Obviously, in this case, most of the gas production potential of the original slurry is lost. The anaerobic filter then becomes merely a method of reducing pollution in the lagoon overflow. The solids in the lagoon digest slowly, and gas escapes to the atmosphere, but it can be collected and used as shown by Balsari and Bozza (1987). Solids may also be allowed to settle in a lagoon or tank and degrade to acids. The tank then becomes part of a two-phase digestion in which the supernatant liquid is converted to gas in an anaerobic filter, (Colleran et al. 1982). There is still a liquid sludge in the tank to dispose of, which may be only partly stabilized.

Separation of solids from animal wastes allows the liquid to be treated in an anaerobic filter, but it removes much biodegradable material. Separation may also be used to remove undegradable material. For instance, Hobson (1987) found that yeast in a whisky distillery spent wash (the residue from the stills) was essentially non-digestible, but its presence caused mechanical problems in digesters. Allowing the yeast to settle out produced a relatively clear liquid which could be treated in filter or UASB digesters. No potential gas production was lost by this separation, and the yeast could be dried for use as cattle feed. Other examples are the separation of solids from palm-oil materials. There is thus good reason for separation and the use of a retained -biomass digester instead of a stirred-tank model. However, mechanical separation is costly in term of capital and running, and separators are not trouble-free. If separation also results in loss of biogas which could be used, then careful consideration must be given to whether the benefits of separation (in the use of a simpler digester for instance) outweigh these increased costs.

Chemical and biochemical treatments of feedstocks

Physical treatments, such as maceration of feedstocks, can increase the rate and extent of bacterial digestion and thus the gas production, but they do not essentially change the chemical composition of the feed. The reason for changing the composition of feedstocks is to break down fibrous materials and produce compounds which are better substrates for microbial growth than the original material. For example, plant materials, either residues in animal excrete or vegetation in energy-crop or plant- waste feeds, can be partly degraded by chemical treatment. Many types of chemical, physical and biological treatments have been applied to plant materials to break down the lignin and make the vegetation more digestible by ruminants (Tagari 1978) and similar treatments could be applied to anaerobic digester feedstocks. The most successful treatments have been those where alkalis, usually ammonia or NaOH, are allowed to react and hydrolyze the solid vegetation for some days at ambient temperatures. Ammonia is used to raise the nitrogen content and decrease the C:N ratio. This type of treatment could be applied to solid feedstocks, such as straw or other plant material. With slurries, it would be difficult to obtain the necessary concentration of chemical (equivalent to a few percent by weight of dry animal feed) to raise the pH sufficiently for alkaline degradation of the lignin to take place, without producing sodium or ammonia concentrations, or an irreversibly high pH, which could inhibit the subsequent anaerobic digestion.

The examples show that some changes may need to be made to digester feedstocks to obtain optimal digestion. These changes may involve the addition of specific chemicals to the feed, but the same changes might be brought about by the addition of an undefined material. Such material may itself be a potential digester feedstock, and mixing may allow better digestion of two or more components of the waste streams. Reactions, such as fermentation of sugars, may go on during the collection process and some alkali or other treatment may be needed before the waste is fed to the digester. Poultry manure, which is rich in nitrogen, can balance a material with low nitrogen content, such as vegetable wastes.

Pretreatment of a feedstock may be inadvertent, in that changes may take place in the feed while it is stored, prior to delivery to the digester. The breakdown on storage of a primary feedstock may be allowed or encouraged, if it results in the production of a substance which itself is a digester substrate. This is the basis for the two-phase digestion of farm wastes. Stopping the natural fermentation of a feed containing easily degraded material like sugars may be difficult, impossible or too expensive, so it may be better to encourage this fermentation to acids to proceed to completion, perhaps by the addition of alkali, to prevent the inhibition of fermentation by low pH. The acid containing solution can then be treated in a retained-biomass digester to give methane. Ensilage is also a natural acid fermentation process, and ensilage of vegetation to store seasonally-produced plants for digestion has been practiced for some years (Stewart 1981). Ensilage produces acids which prevent subsequent deleterious microbial growth, and which can also make the plant fibres more digestible. The acids, along with the solids, can be degraded in the digester after storage. Coble and Egg (1987) ensiled sweet sorghum, which has a high sugar content, but instead of allowing the reaction to stop naturally when the pH had fallen (as happens normally in silage making), they encouraged continual fermentation of the sorghum by connecting the silo to an anaerobic filter, and circulating the silo leachate (plus added water) through the filter and back through the silo.

Digester effluent

As with feedstocks, there should be fewer problems in removing effluents of wastewater digestion from the digester: a U- shape pipe, to retain gas, and gravity flow should suffice. With slurries, weir systems and gravity flow are often sufficient, but if the slurry is thick, or if it has to be moved some distance from the digester for storage or treatment, a pumped output may be better than gravity flow. In general, any treatment which helps the handling of feed will facilitate handling of effluent. Treatment to be applied to effluents depends on many factors. If the effluent is to be used as fertilizer, storage until land and crop conditions allow spreading may be all that is needed. Storage will permit some residual digestion and further reduction of pollutants to take place. With contact type digesters, separation and recycling of digester bacteria is necessary. Separation and recycling of residual solids may help in digestion of recalcitrant materials at a low HRT in a stirred-tank digester. Separation of solids may also be practiced to obtain a solid which can be composted, to be used as soil conditioner, and a liquid which can be used as fertilizer, irrigation water, or recycled to dilute a thick feedstock.

Separation of solids will be necessary if the BOD of the effluent is to be further reduced for river discharge. In the case of a retained-biomass digester, the only separation required is gravity settling of the relatively small amount of biomass which breaks off from the biomass in the digester. In the case of a slurry with undigested solids from a stirred-tank digester, mechanical separation of fibres and sands are required. The liquids can be aerobically treated and filtered, or

further treated, as required by the discharge conditions.

Depending on climate, land available, etc., separated liquids can be used for growing algae, plants, or fish (Marchaim 1983). This will further purify the water and produce an added-value crop. As with the feeds, mechanical separation will produce stackable solids, which can be comported or used immediately as fertilizer or perhaps soil conditioner. Depending on circumstances, it may be possible to use separated effluent solids as protein components for farm animal diets. Since the material has been digested, it is unlikely to contain any substances which are immediately toxic to microbial, plant or animal life. Heavy metals which have been immobilized by precipitation in the digester can be slowly released in fertilized ground or in animal guts, if the effluent is being used as a feedstuff. Such problems have to be borne in mind when the destination of the effluent is being considered.

Control device in an anaerobic digestion process

Anaerobic digestion of organic materials is to be one of the more accepted biomass processes, because it has been in use by numerous municipalities and companies for many years for waste treatment. Over the last two decades, it has been considered and developed for the production of energy; however, the acceptance of the technology for energy production has been limited. The limitations and problems of the process have been the subject of considerable research and development throughout the world; one key topic is the inhibition of the digestion process and its causes.

Ideal indicators for process inhibition should be capable of measuring the progress of sludge digestion, and signal impending upsets before they occur. Common indicators, such as volatile fatty acids, gas composition and pH, are useful for monitoring gradual changes, but do not directly reflect the current metabolic status of the active organisms in the system. They are generally useful for detecting process upsets once they are underway, but in most instances are not adequate to avoid system failure due to difficulties, such as gradual organic or hydraulic overloads.

The mechanism of the rate-limiting step in methane fermentation can be and has been debated, but clearly involves the degradation of volatile fatty acids during methanogenesis, since these acids begin to accumulate in digesters stressed by high organic loading rates and/or short retention times and/or inhibitors (Mackie and Bryant, 1981; Ashley and Hurst, 1981; McInerney et al., 1981). The importance of short-chain fatty acids and alcohols as intermediate metabolites during anaerobic digestion has been well recognized (Smith and Mah 1978). The further degradation of these intermediates relies on dehydrogenation reactions. The energetics of these reactions are only favourable when the concentration of hydrogen is kept very low. The microorganisms that catalyze these dehydrations are considered to be obligate syntrophs, able to grow only in the presence of hydrogen consuming organisms (Bryant et al. 1979, Boone and Bryant 1980, McInerny and Bryant 1981, McInerny et al. 1981). Hydrogen concentrations in anaerobic digestion systems range between 5 - 10 nM when hydrogen-consuming methanogens are active (Poels et al. 1985, Archer et al. 1986, Hickey et al. 1987). An understanding of the close relationship between hydrogen producing and hydrogen consuming organisms has led to the concept of interspecies hydrogen transfer (Bryant et al. 1967, Reddy et al. 1972, Iannotti et al. 1973, Scheifinger et al. 1975, Wolin 1982).

Increases in the concentration of hydrogen would be expected to inhibit the synthropic hydrogen producing partner. For instance, addition of hydrogen to a co-culture of a butyrate- degrader and a methanogen led to the inhibition of butyrate degradation (Ahring and Westermann 1987a, Ahring and Westermann 1987b). It has been suggested that the kinetics of hydrogen consumption controls the bioenergetics and rate of fatty acids oxidation (Dwyer et al. 1988) in defined co-cultures. The exact relationship between hydrogen and fatty acids oxidation remains to be elucidated, but is of critical importance to development of a feedback system based on hydrogen, acetate and propionate monitoring.

This three-step microbial process can work integratively in a digester (the CSTR systems) or can work separately in two (or three) stage digesters, in which the acidogenesis takes place in one digester in its optimal condition, and the effluent is then transferred to the methanogenesis step in another reactor (Cohen 1980; Pipyn and Verstraete 1981). In most industrial uses of anaerobic digestion the CSTR system is used; and a mixed population of acidogenic and methanogenic bacteria is therefore present, such that each probably is not operating in its optimal environment.

It has been shown by several groups that the relationship between methanogenic and non-methanogenic bacteria during the anaerobic digestion i" of great importance, and various growth conditions affect the methane production. For example, when methanogenesis was inhibited, a high volatile fatty acids concentration was observed in the effluent (Sorensen et al. 1981; Ashley and Hurst 1981), the volatile fatty acids being acetic, propionic, butyric acids and others. In many cases described in the literature, unbalanced digestion results in a relatively high concentration of propionic acid, and pH drops below the preferred range. The control of pH is difficult to achieve because of this build-up of volatile fatty acids and, hence, pH control has been only moderately successful.

One of the important ways to control the microbiological process of anaerobic digestion is to control the organic loading to the system (Cohen, 1980). Measurements of volatile acids in good, continuously operating systems show variable levels of acetic acid (according to specific conditions), but very low concentration of propionic acid. It was also shown that during inhibition the level of propionic acid rises, which suggests a shift in microorganism activity. Cohen (1980), working with a physical separation of the acidogens and methanogens by two reactors (each adjusted for optimal conditions) showed that when the first stage digester is overloaded, considerable amounts of propionate and acetate are formed; and, although acetate disappeared rapidly after cessation of the feed, no turndown of propionate was observed. In some cases, accumulation of hydrogen has been noted when inhibition of methanogenesis takes place, while volatile fatty acids also accumulate.

As can be seen from the different biochemical reactions, the important change is in the hydrogen pathway. While hydrogen is generated with acetic acid in the regular pathway of glucose breakdown, hydrogen is consumed in order to produce propionic acid from glucose. The propionate accumulation is probably not a regular intermediate during good steady-state digestion of glucose. Thus, one might view the propionic pathway as a "hydrogen-sink" .

Hydrogen partial pressure (PH_2) exerts significant control on bacterial populations and their Interactions in methanogenic processes. McCarty and Smith (1986), and others, showed that the microbiological population does not appear to utilize the accumulated propionic acid efficiently while rapidly assimilating acetic acid. This leads to a hypothesis that control of an anaerobic digester should strive to prevent the production of propionic acid, because of the microbiological and biochemical shift it implies. Further, the above reactions imply that the key route for achieving this control or stabilization is to alter (decrease) the organic loading when propionic acid accumulation is observed.

Process control

Several concepts of control systems are known and used, especially in the chemical industry, such as those described by McClain and Goswami (1979) (closed loop system, pacing system, and ratio control system). There is a need to improve existing anaerobic digester control systems and develop better ones, incorporating such concepts applied in other industries.

This need was amply illustrated by the number of times that the topic was questioned and discussed at various International symposiums on anaerobic digestion - AD83, AD85, AD88. The general consensus seemed to be that the usual control parameters (e.g. pH control; Schaffer and Casciano 1979) were not sufficient, or the measurement was not reliable. It must be noted that none of the usual analysis/control schemes provide a direct link to the biochemistry related to the microbiology of the digestion system. Thus, what appears to be needed is a control system which is more closely related to the biochemistry of the digester, and which employs reliable analytical approach and equipment.

Since 1985, studies have been conducted by Hickey and colleagues (1988) to evaluate the efficiency of hydrogen and CO as a means of monitoring anaerobic systems, under steady state conditions, in response to organic overloads and in response to toxic or inhibitory shocks induced through the application of organic and inorganic toxicants. The long range primary goal of this research was to use this information data base to assist in developing more sensitive and effective process control strategies, that will minimize the time interval between the impending upset and its actual occurrence. This will allow more time for remedial measures, and help to eliminate or alleviate the severity of an oncoming upset. It was found that the impact that the toxins (and organic overloads) had on the system were concurrently assessed by more

conventional parameters (gas production, methane and carbon dioxide composition, VFA and pH), to allow a comparison of the various parameters.

A large data base on the response of the anaerobic sludge digestion systems to overloading and toxic inputs has been generated. Results have been published on the effect of organic toxicants (Hickey et al. 1988) in terms of hydrogen response. The conventional parameters show a slow deterioration in process performance. The VFA/TA ratio was the first to register a possible upset condition. Gas production and carbon dioxide/methane content did not show any definite indication of upset until a few days later. Hydrogen and CO, however, demonstrated a significant initial response to increase in organic loading. A strong correlation between CO and acetate is apparent from the data. It also appears that there may be some correlation between hydrogen concentration and gas production rate, as has been suggested (Mosey 1983).

To summarize world efforts up to the present time, monitoring intermediate trace gases and volatile fatty acids can provide some measure of the metabolic status of an anaerobic system. In contrast to liquid phase sampling, gas analysis. is amenable to real time data acquisition. Using a tiered experimental plan, the response of systems due to toxic upsets and variations in hydraulic and organic loading has been studied along with more conventional parameters of digester stability. Based on these studies, it appears that monitoring both hydrogen and CO together, and volatile fatty acids, may lend significant insight into the metabolic status of the digestion process and has the potential to indicate process upsets on a real-time basis. The exact relationship between hydrogen and fatty acids oxidation remains to be elucidated, but is of critical importance to development of a feedback system based on hydrogen, acetate and propionate monitoring. It has been shown by several groups that the inter-relationship between methanogenic and non-methanogenic bacteria during anaerobic digestion is of great importance, and various growth conditions affect methane production. For example, when methanogenesis was inhibited, a high volatile fatty acids concentration was observed in the effluent (Sorensen et al. 1981; Ashley and Hurst 1981), namely acetic, propionic, butyric acids and others. In many cases described in the literature, unbalanced digestion results in a relatively high concentration of propionic acid; and pH drops below the preferred range. The control of pH is difficult to achieve because of this build up of volatile fatty acids, and hence, pH control has been only moderately successful.

Experiments were performed by Marchaim and Krause (1991) in order to examine the possibility of controlling the anaerobic system by monitoring the acetic to propionic acids ratio. In the Marchaim and Krause experiment, the system consisted of an anaerobic digestion system with a steady pH level (approximately pH 7). Changes in the rate of feeding with glucose, were made in several digesters, in order to compare the ratio of propionic to acetic acids in the overloaded digesters, which were operated under identical conditions.

The fact that the ratio of propionic to acetic acid showed an increase immediately after raising the concentration of feeding, and prior to any changes in biogas composition, suggests that the ratio of propionic to acetic acid in an anaerobic digestion system is a satisfactory real-time indicator for the beginning of organic overloading.

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Chapter eight: Output and its use I

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Biogas as an alternative energy source

The proportion of methane to carbon dioxide in biogas depends on the substrate, and can be predicted by Symons and Buswell's equation. Factors such as temperature, pH and pressure can alter the gas composition slightly.

Typical gas compositions for carbohydrate feeds are 55% methane and 45% carbon dioxide, while for fats the gas contains as much as 75% methane.

Pure methane has a calorific value of 9,100 kcal/m^3 at 15.5°C and 1 atmosphere; the calorific value of biogas varies from 4,800 - 6,900 kcal/m^3 . In terms of energy equivalents, 1.33 - 1.87, and 1.5 - 2.1 m^3 of biogas are equivalent to one litre of gasoline and diesel fuel, respectively. Biogas has an approximate specific gravity of 0.86 (air = 1.0), and a flame speed factor of 11.1 , which is low, and therefore the flame will "lift off" burners which are not properly designed, i.e. become unstable because of its distance from the burner (ESCAP 1980).

Domestic uses

The primary domestic uses of biogas are cooking and lighting. Because biogas has different properties from other commonly used gases, such as propane and butane, and is only available at low pressures (4 -

8 cm water), stoves capable of burning biogas efficiently must be specially designed. To ensure that the flame does not "lift off," the ratio of the total area of burner parts to the area of the injector orifice should be between 225 and 300:1 (FAO 1981). Recent Indian designs have thermal efficiencies of around 60% (Mahin 1982). In China the Beijing-4 design has a thermal efficiency of 59 - 62%, depending on the pressure (Chan U Sam 1982).

Lighting can be provided by means of a gas mantle, or by generating electricity. Highest lamp efficiencies require gas pressures of 40 cm, which are only possible with fixed dome digesters.

Reported gas consumption for cooking and lighting is 0.34 0.41 m^3 per capita/day and 0.15 m^3 per hour per 100 candle power respectively (NAS 3 1977). A typical family of six uses approximately 2.9 m $^{3/}$ day of biogas.

Agricultural and industrial uses

Biogas can be used as a fuel in stationary and mobile engines, to supply motive power, pump water, drive machinery (e.g., threshers, grinders) or generate electricity. It can be used in both spark and compression (diesel) engines. The spark ignition engine is easily modified to run on biogas by using a gas carburettor. Ignition systems need not be altered, other than minor timing adjustments. At the standard compression ratios, a decrease in power results. Supplementary fuels can be used with biogas in spark ignition engines.

Where the biogas supply varies or there is only a small quantity available, dual fuel diesel engines have been used successfully. Normally the modifications are simple. The engine is usually started with pure diesel fuel and the biogas increased gradually until it comprises around 80% of the fuel intake. If the gas supply is interrupted, normal operation can still proceed with up to 100% diesel fuel. With 80% biogas, engine performance is good and 20% more horsepower is delivered than with diesel alone (Sharma 1980).

The normal thermal efficiency of these engines is 25-30%, and they use approximately 0.45 m of biogas per horsepower-hour. Converting this to electricity, approximately 0.75 m^3 of biogas is required per kilowatt hour. There were 301 small biogas power stations in China at the end of 1979, generating 1,500 kw in Sichuan Province alone. A recent report describes a 9000 kw station operating on biogas from nightsoil digestion (National Office for Biogas Development 1982).

Due to the low thermal efficiency of these engines, a large fraction of the biogas energy can be recovered from the cooling water and exhaust gases. This energy can be used to heat the digester, or for space heating of animal sheds, greenhouses and buildings.

A problem in the use of biogas in internal combustion engines is that the hydrogen sulphide in the gas is

corrosive. However, in China engines were run for five years with no internal corrosion (Chan U Sam 1982). In general, the operating lives of the engines are expected to be between 12,000 and 20,000 hours, depending on the engine speed and horsepower (Picker and Soliman 1981).

Use of biogas for vehicle fuel

Biogas is suitable as a fuel for most purposes, without processing. If it is to be used to power vehicles, however, the presence of CO_2 is unsatisfactory, for a number of reasons. It lowers the power output from the engine, takes up space in the storage cylinders (thereby reducing the range of the vehicle), and it can cause problems of freezing at valves and metering points, where the compressed gas expands, during running, refuelling, as well as in the compression and storage procedure. All, or most, of the CO_2 must therefore be removed from the raw biogas, to prepare it for use as fuel for vehicles, in addition to the compression of the gas into high-pressure cylinders, carried by the vehicle.

The simplest and cheapest method of removing the CO_2, is by washing the gas with water under pressure. This process can be conveniently integrated with compression, using a 3 or 4 stage compressor, and can easily be automated, as in the Invermay "energy farm". This method of scrubbing the biogas is capable of producing 100% pure methane: the Invermay system produces 95% pure methane from raw biogas, originally containing 55% methane, which is pure enough for vehicle fuel. The scrubber also removes all corrosive sulphides.

It is convenient to modify vehicles to use methane as fuel in such a way that they can continue to use conventional fuel when outside the range of a gas refuelling station. Equipment designed for conversion of petrol engines to use natural gas or petrol is readily available from a number of manufacturers in Italy and the U.S.A.; and the same equipment can be used for conversion to methane or biogas. Since natural gas contains some higher alkanes (ethane, propane, butane, etc.) besides methane, giving the gas a higher energy than methane alone, larger diameter gas inlet supply lines and jets are needed for optimal running on methane. These modifications are especially important in the case of biogas containing less than 100% methane.

If the gas is introduced to the carburettor via a spacer and inlet pipe, fitted between it and the air cleaner, it is also essential that the hole in the spacer, through which the air flows, is of a suitable size and design to draw in the gas also, by the venturi effect.

Even when the conversion is made correctly, there is likely to be some loss of power when the engines runs on methane or biogas instead of petrol, because of the compromise required to adapt the engine to use both fuels interchangeably. This loss in power can be compensated for by increasing the compression ratio of the engine, to take advantage of the higher octane rating of methane, but then the engine can no longer run on petrol.

The purification of biogas

Hydrogen sulphide (H$_2$S) is particularly harmful when biogas is used in internal combustion engines. Its chemical reactions and those of its combustion product - sulphur dioxide - lead to corrosion and wear on engines. The only practical way of removing the hydrogen sulphide on a small scale is by dry desulphurization, using ferrous substances. Locally available, iron-containing soil is suitable for use as the purifying agent in Developing Countries. This chapter contains a detailed description of criteria for designing the purification chamber. It also presents the basic steps for manufacturing the purifying agent or absorbent.

Physical and chemical properties of hydrogen sulohide

Hydrogen sulphide is a colourless, very poisonous gas. It is inflammable, and forms explosive mixtures with air (oxygen) H$_2$S has a characteristic shell of "rotten eggs", apparent only in a small concentration range (0.05 - 500 ppm). It is soluble in water, forming a weak acid. A combustion product of H$_2$S is SO$_2$, which makes the exhaust gases very corrosive (sulphuric acid) and contaminates the environment (acid rain). H$_2$S is very poisonous (comparable to hydrogen cyanide): with a lower toxic limit of 10 ppm. 1.2 - 2.8 mg H$_2$S per litre of air (0.117%) kills instantly, 0.6 mg H$_2$S per litre of air (0.05%) kills within 30 minutes to one hour. H$_2$S changes the red blood pigment; the blood turns brown to olive in colour. The transport of oxygen is hindered. The person suffocates "internally". The symptoms are irritation of the mucous membranes (including the eyes), nausea, vomiting, difficulty in breathing, cyanosis (discoloration of the skin), delirium and cramps, then respiratory paralysis and cardiac arrest.

At higher concentrations immediate respiratory paralysis and cardiac arrest are the only symptoms. Even if a person survives poisoning, long term damage to the central nervous system and to the heart may remain.

The origins of hydroqen sulphide in biogas plants

Hydrogen sulphide is formed in the biogas plant by the transformation of sulphur-containing protein, which can be from plants and fodder residues. However, when animal and human faces are used, bacteria excreted in the intestine" are the main source of protein. Inorganic sulphur, particularly sulphates, can also be biochemically converted to H_2S in the fermentation chamber. While plant material introduces little H_2S into biogas, poultry droppings introduce, on average, up to 0.5 volume percent of H_2S, cattle and pig manure about 0.3 volume/percent. Protein-rich waste (e.g. molasses, etc.) can produce large amounts of hydrogen sulphide (up to 3 vol. %). Inorganic sulphates (from salty, stall rinse water or diluting water) also produce considerable H_2S.

The effect of H_2S on the biogas plant and the gas-utilization equipment

Dissolved H_2S is contained in the fermentation slurry, and when dissolved in high concentrations can be toxic to the bacteria in the slurry. It can inhibit the production of biogas and cause its composition to alter. This can be remedied by putting less sulphur-rich material in the plant or diluting with water. In less serious cases, stir vigorously to drive H_2S out of the slurry. The presence of H_2S gas in biogas makes it corrosive to metal parts: iron and galvanized parts are subject to surface attack, although not to major corrosion. The effect on non-ferrous metals in components, such as pressure regulators, gas meters, valves and mountings, is much more serious.

The combustion product, SO_2 combines with water vapour and badly corrodes the exhaust side of burners, gas lamps and engines. Burning biogas in stoves and boilers can also result in damage to the chimney.

Engines

The acid which is formed corrodes engine parts in the combustion chamber, exhaust system and in

various bearings. This is enhanced by frequent starts, short running times and the relatively low temperatures when starting up and after cutting off the engine. The water cooling system also provides the means (water needed to form sulphuric acid) for corrosion. Running engines with gas containing H_2S can reduce the service time to the first general overhaul by about 10 - 15%. The sulphur content of biogas used in gas engines shortens the time between oil changes and overhauls. SO_2 from combustion and water vapour both dissolve in the lubricating oil. The oil becomes acidic, and its properties change, losing its ability to lubricate and sometimes corroding metal components. Under continuous operating conditions, the interval between oil changes is reduced to 200 - 250 hours. If biogas is burned for cooking and lighting in poorly ventilated rooms, the occupants will be burdened by SO_2 in the air.

Indicators are coughing, irritation of the mucous membranes, watering of the eyes and the corrosion of metal surfaces.

The odour of biogas

Adequate desulphurization of biogas causes it to lose its characteristic, warning smell. This increases the danger of unnoticed leaks from pipes or equipment. SO_2 formed during combustion pollutes the environment by creating "acid rain". Even small concentrations of SO_2 in the atmosphere damage plants. Its concentration in the soil slowly causes land which is lacking in lime to become acidic. These effects should be negligible when biogas is used in rural areas in Developing Countries, since only small amounts of biogas are produced.

As noted, the desulphuring of biogas is necessary for its use in gas engines. Under some circumstances it is expedient to desulphur for boders. Desulphurization is also required when the biogas is produced from sulphur-rich materials. If people are not adversely affected, desulphuring is not required when biogas is burned openly.

Determination of the H_2S content of biogas

The H_2S content of the purified gas can be measured to check the effectiveness of the desulphuring process. In the laboratory, the H_2S content of gases is usually measured iodometrically, using cadmium acetate. However, the necessary techniques are too involved for application in the field.

A simple way to determine the presence of H_2S in biogas is a test with lead acetate paper: when a piece

of paper soaked with lead acetate solution is held in the gas stream for a short time, the presence of H_2S colours the strip black. The difficulty with this method is its high sensitivity, since a small amount of H_2S is not an indication of greatly reduced efficiency of the desulphurization. Simple desulphuring plants may still posses an adequate purifying performance.

Another method for detecting H_2S is with an alcoholic solution of iodine, such as often available in first aid kits. A small amount of biogas is carefully introduced into the iodine solution. If H_2S is present the reddish brown solution will decolour, causing a milky turbidity.

The test-tube method is a very exact and simple method of determining the H_2S concentration in biogas. Suitable tubes are available for measuring the concentration in both raw and purified gas. However, the gas detector apparatus and the individual test tubes are relatively expensive. Also, the test tubes can only be preserved for a limited time. This method is only expedient in the regional biogas extension service or similar advisory services. The apparatus can then be used to provide empirical field values for individual plants. The intervals for recharging the purifying agent can then be laid down.

As yet there is no simple, cheap, test method available. For this reason a close control of the desulphuring plant is strongly recommended.

Methods for removing H_2S from biogas

Of the many processes traditionally and presently employed that have been used for large-scale desulphurization of gases, only the so-called "dry" process is suitable on a smaller scale for biogas plants. The desulphuring of biogas is based on a chemical reaction of H_2S with a suitable substance, such as quicklime, slaked lime in solid form, or slaked lime in liquid form. The process using quick or slaked lime has not been applied on a large scale for a long time, because the large amount of odorous residue that is produced cannot be satisfactorily disposed of. Large concentrations of CO_2 which are present in biogas make the satisfactory removal of H_2S difficult: the CO_2 also reacts with the quick and slaked lime and uses it up quickly. The $Ca(HCO_3)_2$ formed reacts with $Ca(SH)_2$ which is formed by the reaction of H_2S with $Ca(OH)_2$ thus resulting in the recurrence of H_2S. A large scale biogas plant in Germany, with the co-generation of heat and power, has recently been constructed, using a lime purifier, but the results of long term tests are not yet available. In as far as enough lump quicklime is available in the countries concerned, this process could be considered for desulphurization. The apparatus for utilizing quicklime corresponds in construction and function to that used for the desulphurization with iron- containing substances.

Ferrous materials in the form of natural soils or certain iron ores are often employed to remove H_2S. The ferrous material is placed in a closed, gas-tight container (of steel, brickwork or concrete). The gas to be purified flows through the ferrous absorbing agent from the bottom and leaves the container at the top, freed from H_2S.

The absorbing material must contain iron in the form of oxides, hydrated oxides or hydroxides. This process terminates, of course, after some time. The greater part of the iron remains as a sulphide.

Regeneration

However, by treating the sulphided absorbent with atmospheric oxygen, the iron can be returned to the active oxide form required for the purification of the gas. The used absorbent can, therefore, be "regenerated". This regeneration cannot be repeated indefinitely. After a certain time the absorbent becomes coated with elementary sulphur and its pores become clogged.

Purifying absorbents in gasworks (coke plants) acquire a sulphur content of up to 25% of their original weight,

There are three different, dry desulphuring processes available:

Without regeneration The purification chamber consists of a box or drum. The absorbent is placed inside it on several, intermediate trays (sieve floors) to ensure that the depth of the absorbent is not more than 20-30 cm. The biogas is fed in at the bottom of the box, flows through the absorbent and leaves the purification chamber at the top, freed from H_2S. When the absorbent becomes loaded with iron sulphides, the gas leaving the chamber contains more and more H_2S. The chamber is then opened at the top, the trays with the spent absorbent are removed, and then fresh absorbent is placed on the trays. After the air in the purification chamber has again been displaced with biogas the gas connection to the user is re-opened.

With regeneration The spent, sulphide-containing absorbent can also be regenerated by exposing it to oxygen. This can either be done by taking the used absorbent out of the chamber and exposing it to the air, or inside the purification chamber by simply sucking ambient air through it.

Since regeneration inside the chamber requires precautions against the formation of unwanted and dangerous air-gas mixtures and would require powerful fans, regeneration outside the chamber is usually preferred. The absorbent that is to be regenerated is spread out on the ground in as thin a layer as possible. From time to time it is turned over with a shovel. After a few days it is ready for use again. This regeneration process can be repeated up to ten times, after which the absorbent is finally spent.

Simultaneous regeneration and loading Simultaneous regeneration and loading of the absorbent is a special case. Here, a small amount of air is added to the biogas, so that sulphide formation and regeneration occur at the same time and place. The absorbent acts effectively as a catalyst. Expensive gas-measuring and mixing equipment is required for this process, however, so that it is not suitable for small biogas plants.

Alongside the traditional, commercially available absorbents, certain substitutes can be used. Various tropical and subtropical soils contain sufficient iron in a suitable form, but must be prepared to obtain the proper purifying characteristics. The material must be loose, porous, moist and granular. The raw soil has to be ground and mixed with a filler and water to obtain a homogeneous texture. Using two or more purification chambers, connected in series, ensures a continual production of purified gas, and allows a good capacity utilization. The spent absorbent can be disposed of safely by burying it. Various factors must be considered in calculating the dimensions of the purification chambers. A certain maximum flow speed should not be exceeded. The gas volume to be purified, per unit time, determines the cross section of the purification chamber. The chamber volume, and hence, the amount of absorbent, determine the operating time for the purification process before regeneration or exchange of the absorbent. A calculation procedure simplifies working out the dimensions of the desulphuring unit.

Biogas production and utilization in China

Gas production of all household digesters in China totals about 2,000 million m^3 per year. In southern China, the total gas yield of family size digesters averages 300 m^3 per year (over 8 months). In the north, production is 200 m^3 biogas per year, or less, depending on ambient temperatures. Biogas production in RMP plants is usually 10% higher, due to the heat absorption effect.

Biogas in China is used by about 25 million people for cooking and lighting for 8 - 10 months a year. Many rural households are equipped with both biogas stoves and improved cooking stoves. With the latter type, the peasants burn straw and wood, as usual, during the winter months, for cooking and heating. Improved and cheap biogas stoves and lamps have been developed and are distributed to every biogas owner. The cost of one biogas lamp varies between 6 - 12 Yuan. Lamps and burners are adapted to low pressures of about 2 cm, at which RPM digesters operate. Commercial and industrial burners are also being investigated in China. Furthermore, the use of biogas is manifold: There are about 400 biogas power stations, with a total capacity of 5,800 HP, 800 biogas electrical stations with a total capacity of 7,800 kw, providing electricity to over 17,000 households. China has sound experience in running diesel and gasoline engines with biogas.

The net energy obtained by anaerobic digesting plants refers to the difference between total energy (biogas) generated during the process of anaerobic digestion and the energy consumed during the process in maintaining anaerobic digestion. This value is a key to achieving profitability.

The net energy output of mesophyllic anaerobic digesting installations serves as an important criterion for measuring their economic effects. In his case study on the 3-year operation of the biogas plants at Gold Star Dairy Farm and Nan-ge-zhuang Fish Farm in Beijing, Tang (1989) analyzed the factors that affect the output of total energy (biogas output), such as types of manure, technological process, and means of stirring. He studied the factors that consume energy in maintaining a mesophyllic operation, such as heating the slurry, heat dissipated from digesters and their pipes, and the energy consumption of various apparatus, in particular the pumps. Through this analysis of various energy consuming factors, their proportion in energy consumption was obtained.

Use of biogas in India

Biogas is commonly used for cooking and lighting: there are a number of enterprises in each State that produce stoves and lamps. At some Community and Institutional Biogas Plants, biogas operates engines or agricultural equipment. Only three enterprises in India manufacture or adapt diesel engines with optional operation on biogas.

Activities in using biogas in India have gained momentum since the National Project on Biogas Development was launched in 1981 and the Department of Non-conventional Energy Sources in 1982. Today, it is generally accepted among richer farmers that a biogas plant is desirable. The earlier period was taken up with problems, such as convincing bankers to give loans and setting up the organizational structure, subsidy system, etc.

The introduction of biogas technology in the rural areas of India requires technological improvements and financial help for successful operation. The technological improvements should be:

(a) To nullify the effect of low temperature on gas production;
(b) To devise simple, economical and labour-saving equipment for dung collection;
(c) Effective techniques for drying and transporting the effluent.

During the initial stages, the Government may provide the funds to meet the operational losses, so that the technology may be absorbed by the rural masses. Intensive efforts are made to upgrade technology, to produce more gas without excessive sophistication.

Experience of full scale plant of biogas generation at Hambran, Punjab

To save commercial energy, prevent deforestation, reduce soil erosion and preserve organic biomass for recycling, and to produce more food grain, a comprehensive program for the use of non-conventional

energy was introduced by the Government of India. Special emphasis was laid on the biogas program. In the first phase, stress was laid on the family size biogas plants, but later emphasis was shifted to the installation of community/institutional biogas plants to provide cheap and smoke- free cooking gas to the rural populace who can not install their own plants, due to poverty, lack of dung and land for installation of the digester. The DNES, Government of India, provided a 10% subsidy for the installation of community biogas plants. There were 20 community biogas plants in operation and several more under construction in the State of Punjab in 1988. In India there were over 250 community/ institutional biogas plants in operation. Production of biogas during the winter, costly dung collection arrangements, inadequate slurry handling systems and lack of outside financial help are some of the constraints in the promotion of the program.

Vyas et al. (1989) examined a community biogas complex that had been installed at the village of Hambran, Punjab, to study aspects of the introduction of biogas technology into rural households. The village had 293 households, with a human and animal population of 1711 and 1400 respectively. An area of 936.4 ha was under cultivation, out of total geographical area of 1136.6 ha, with mechanical and electrical power inputs of 0.58 and 0.06 kw/ha respectively, plus animal power. The main occupation of the households was agriculture, followed by agricultural labour. The average family had 5 members. The households used cow dung cakes, fuel wood and agricultural waste as cooking fuel. The specific objective of the study was to collect information about the technical, social and economic feasibility of the community biogas plant.

The plant consisted of 4 floating drum digesters, with an average gas production capacity of 505 m /day, together with the necessary infrastructure, such as dung collection platform, mixing chamber, silt excluder, slurry inlet pipe line, slurry outlet, slurry recycling system, a pump for slurry storage, slurry handling machine, latrine block, generator room, wind mill and drying beds. The digesters had special constructional features: doubly reinforced raft foundation, reinforced brick walls, elimination of steel frame by a central pillar as guide pipe, no diametric dividing wall, two concentric well digesters with an outer to inner diameter ratio of 1:8, diameter depth ratio of 1:35, 3 outlets per digester, and provision for the installation of stirring and heating arrangements. The biogas was supplied to individual households by a pipe line. The plant was put into operation in 1986. People's participation in the community work was the main prerequisite for the success of entire program and needed careful planning at all stages. An association of users was formed and registered. A managing committee of 8 members was elected for the day to day management of the plant, aided by professors from the University.

Effect of temperature variation on gas production

The variation in the mean ambient temperature from 32.9-12.7°C, during the year 1986-87, affected gas production. The coefficient of correlation between gas production per unit of input and ambient temperature was 0.92.

The reduction in gas production forced the management to reduce the hours of gas supply. Dung supply from the consumers was also closely correlated to the ambient temperature (r=0.89). With the fall in the mean ambient temperature from 32.9°C in July to 12.7°C in January, the gas supply time decreased from 6.5 to 3.00 hours and the dung supply correspondingly decreased sharply from 39 to 18 quintals per day (1625 - 750 kg/day). Similarly, with the rise in ambient temperature from January onwards, both the gas supply time and dung supply touched the previous level. The reduction in gas supply time affected the income of the plant adversely, because gas charges per connection had to be reduced in proportion to the duration of gas supply, while operational costs remained the same.

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Chapter nine: Output and its use II

Digested slurry: the profit lies in the use of the effluent

Economic evaluation studies have shown the importance of using the digested slurry after the anaerobic digestion process, as well as the biogas. Marchaim et al. (1981ab, 1983), as well as other groups in other countries, described the main uses of digested slurry, before and after separation. The economic importance of the digested slurry is becoming more acceptable in recent years in the Developing Countries as well, and this concept is presented in many publications of China, India and other countries. What follows is a summary of some of the commoner uses of the digested slurry, and the main research done in this topic, with the economic emphasis on its uses.

The slurry discharged from a digester contains 1 - 12% solids and consists of refractory organics, new cells formed during digestion, and ash. The slurry can be used in its liquid or solid fractions, dried or as total slurry.

Components of slurry which provide fertilizer and soil conditioner properties are soluble nutrients and trace elements, insoluble nutrients, and the organics present in the solids (humic materials). The components of a specific digested material are similar in content, despite other differences, to the raw material used for the digestion process, and must be examined according to the original materials uses and value. The uses of slurries without anaerobic digestion is still very common in many countries, and its value can not be ignored (Vetter et al. 1988).

Biomass uses without anaerobic digestion

There are many possible ways in which biomass resources can be used. The most efficient way of using cattle manures is to provide fertilizer, soil conditioner and/or fuel from a given amount of biomass. The processes described occur to a lesser extent with vegetative waste materials and other biomass resources. In most cases attention is paid especially to nitrogen content since this element is usually important in terms of both quantity and effect on crops.

Biomass can be used for:

      a. burning;
      b. applying to the field surface;
      c. applying to the field and ploughing under;
      d. comporting and applying to the field;

The effect of use on the nitrogen present in the biomass is discussed below.

Option A: Burning is common in many developing countries, and results in the complete loss of nitrogen, through volatilization and mineralization. Phosphorus, potassium and the trace elements remain in the ash. The biomass is often burned in traditional three-stone fires which have a thermal efficiency of 10 - 15%. Recently (especially in China and India) an improved stove is used, and the efficiency can reach 30%. Burning leaves virtually no fertilizer, and the traditional fuel efficiency is considerably lower than for biogas produced from the same amount of biomass. This use of biomass meets acute energy needs of people, but ignores global needs for fertilizers.

Option B: Applying biomass directly to the field surface is practiced in most countries (Vetter et al. 1988), and the fate of the nitrogen depends on the composition of the biomass. Nitrogen is present in animal manures in two forms: organic and ammonia. In most other sources of biomass it exist in smaller quantities, and as organic matter. Most organic nitrogen is in the form of proteins and nucleic acids, while the ammonia nitrogen is present as either the ion, NH_4, or free ammonia, NH_3. For fresh cattle manures ammoniac nitrogen can vary from a low of 3% (Idnani and Varadarajan 1974) to 20% (Hamilton Standard 1980), or even as high as almost 40% (Hashimoto et al. 1981a). For dairy manure, equivalent figures are 24% (Hart 1963) and 37.6% (Jewell et al. 1976); for pigs, around 18% (UNEP 1981); and for fresh chicken manure, 8%.

When fresh manure is spread on the surface of a field, almost all the ammonium nitrogen is lost through volatilization. Direct field application is not an efficient use of biomass resources (Vetter et al. 1988).

Option C: Ploughing fresh manure into the field prevents loss of ammonia through volatilization, and almost all the nitrogen is conserved. However, under certain conditions, organisms can nitrify free ammonia to nitrite (NO_2) and nitrate (NO_3). These ions are relatively soluble and can be leached from the soil. Implementation of this option is relatively time-consuming, especially if the biomass is manure that i" produced daily, and its application is infrequent. Storage of the biomass is necessary in winter, and a large percentage of the nitrogen can be lost to the atmosphere if storage conditions are not suitable.

Option D: Composting is a common way of recycling biomass in Developing Countries, as well as in Developed Countries. The biomass is piled in a heap (agricultural residues are mixed with animal manure) and left to decompose aerobically. The pile is occasionally turned over or otherwise aerated. Compost may be stored for an long period of time before it is applied to the field. The composted biomass has few degradable organics, is essentially inoffensive to handle, is reduced in volume, and does not attract flies or other insects. However, there is a loss of nitrogen during composting and storing. Data on nitrogen loss reported by Gunnerson and Stuckey (1986) is listed in Table 9.1.

Table 9.1: Nitrogen Loss due to Composting or Digestion

Field Practice	Nitrogen Effectiveness Index (%)
Manure spread and ploughed in immediately	100
Effluent from digester, introduced immediately into irrigation water	100
Dried digester plant effluent spread and ploughed in	85
Manure piled 2 days before spreading and ploughing in	80
Manure piled for 14 days	55
Manure piled for 30 days	50

For an optimal use of slurry, it is very important to calculate the correct nutrient content. Under optimal conditions the efficiency of pig and poultry slurry nitrogen application can be as high as 60 - 80% of an equivalent amount of commercial nitrogen fertilizer in the first year of application. Cattle manure efficiency is normally at the range of 30 - 50%. Since part of the organic nitrogen is released in subsequent years, the nitrogen efficiency, in the long run, reaches almost 90% of inorganic nitrogen. Detailed attention must be paid to problems of hygiene and odours.

Biomass uses following anaerobic digestion

Anaerobic digestion provides both fuel and fertilizer, while options A - D above provide either one or the other, but not both. Nitrogen can be lost during digestion only by reduction of nitrates to nitrogen gas and volatilization of ammonia into the biogas. Since there is very little nitrate present in manure, such loss through reduction is insignificant. Loss of nitrogen through volatilization of ammonia can occur from the slurry if not

handled correctly.

Since organic matter is degraded during digestion to produce biogas, the percentage of nitrogen in the slurry rises, compared with solid content. Nitrogen is conserved during anaerobic digestion. For example, a 23% reduction in total solids concentration is accompanied by a corresponding increase in the nitrogen content of the remaining solids. This may create an illusion of "new" nitrogen, if only the total Kieldahl nitrogen (TKN) is considered. Jewell et al. (1976) found that the TKN for dairy manure increased from 5.2% - 6.9% of the solids during digestion and Hart (1963) found increases from 3.7% to 3.9% of the solids. Rajabapaiah et al. (1979) also carried out detailed mass balances on a KVIC digester and found that nitrogen was conserved.

The ammonia fraction of the TKN in digester slurry has an important influence on its fertilizer value, since ammonia is the form of nitrogen most easily taken up by plants. In its organic form the nitrogen is released more slowly, and some fraction may not be degraded, thus being unavailable to plants. With animal manures, the ammonia nitrogen concentration increases during digestion: Jewell et al. (1976) found that the ammonia nitrogen in dairy manure increased from 37.6 - 44.6% of the TKN during digestion. Similarly, Hart (1963) found an increase of from 24.0 49.0% during digestion.

The chemical composition of materials loaded into the anaerobic methanogenic thermophilic digestion system, and of the digested slurry obtained from this continuous process, is presented in Table 9.2. The breakdown of organic material was over 25%.

Table 9.2: Chemical composition of input materials and digested slurry out-put of the methanogenic fermentation system at a slaughterhouse

	Input Material	Digested Slurry
pH	6.32 + 0.38	7.40 + 0.21
Solids (%)	15.44 + 2.04	11.28 + 1.51
Ash (%)	1.96 + 0.53	1.76 + 0.27
Ammonia (g/l)	0.62 + 0.18	0.87 + 0.26
Nitrogen (g/l)	2.70 + 0.35	1.95 + 0.27
Phosphorus (g/l)	3.26 + 0.55	2.43 + 0.27
Volatile Acids (g/l)	6.73 + 1.53	3.44 + 1.83

*Average of 12-15 analyses; analysis was carried out regularly, once every 2 weeks (Marchaim et al. 1991).

Land application of effluent

The direct application of manure to the land is the commonest single technique for its disposal and use in the world. It improves filth, increases water-holding capacity, lessens wind and water erosion, improves aeration,

promotes the growth of beneficial organisms and maintains soil fertility. The economic value of manure as a fertilizer is calculated from its available nitrogen, phosphorus and potassium content, and as a soil conditioner: the same criteria are applied to the effluent generated by the biogas plant.

Manure contains many salts that are included in the cattle ration or consumed in the water. Heavy application of manure can increase the accumulation of soluble salts in the soil (i.e. its salinity), especially in arid regions, and these must be leached from the crop root zone, normally through under-drainage. The greater the amount of manure applied to the land, the greater the quantity of water needed for leaching, without which the salinity of the soil will be enough to inhibit plant growth and lessen yields. Salts are, in fact, the principal limiter in the application rate of manure to crop land, and salinity has become an acute problem in heavily cultivated areas.

During the biogas digestion process, water-soluble salts are dissolved into the aqueous solution. Here they are evenly distributed, and only approximately 30% of the solution accompanies the coarser fraction ("cabutz" or "biosolids") after separation. Hence, the solids have a lower salt content than the original manure, the rest being concentrated in the liquid fraction.

In most countries where biogas plants were constructed, the effluent was used as a fertilizer. The use of the effluent was extensively studied by institutes in the Republic of China, and they found chemical changes in the organic substances during fermentation. According to studies in Sichuan Province (1979), the nutrient contents of the effluent increased yields by 6 - 10%, regardless of kinds of soil; the same results have been reported by groups in other parts of the world. In long-term experiments, it was shown that the chemical and physical properties of the soil were improved markedly, after a few years of applying digester effluent, while total yields of several crops were 11 - 20% higher than controls. The NEFAH group (Marchaim and Criden 1981; Marchaim 1983) found that there was no clear difference between compost and effluent treatments, but that slurry did not increase the salinity of the soil, and reduced residual effects in the long term. Digestion followed by drying results in the loss of great amount of the ammonia. Jewell et al. (1981) found that 35% of the ammonia nitrogen was lost during drying over 72 days (see Table 9.3). The amount of ammonia nitrogen lost during drying will depend on a number of factors such as its concentration in the slurry, the pH of the solution, and the temperature of drying. This is also true sun-drying.

Table 9.3: Ammonia losses from Stored Mesophyllic Effluent (g/l)

Time (day)	Total Solids	NH_4^+	NH_3^-
1	90.4	3.319	0.328
8	91.7	3.261	0.322
16	92.5	3.019	0.241
23	92.5	3.086	0.246
30	95.8	2.695	0.174
36	97.0	2.701	0.173
43	96.7	2.301	0.161
49	98.3	2.450	0.157

| 65 | 100.4 | 2.186 | 0.113 |
| 72 | 98.1 | 2.260 | 0.117 |

Reference: Jewell et al. (1981)

Analysis of the benefits of anaerobic digestion based on nitrogen alone tends to neglect humus, micro-nutrients, trace elements and water in the slurry. Taking these factors into account, the value of digested slurry may be considerably higher than an analysis based only on nitrogen indicates.

Table 9.4: Estimated quantities of manures or fertilizers needed to supply 1 kg nitrogen to any given area of cropland

Nitrogen availability	Quantity 100%	needed 50%	(kg) 25%
Ammonium phosphate	9		
Ammonium auperphosphate	33		
Ammonium aulphate	5		
Urea	2		
Cattle dung (fresh)	34	690	1,380
Cattle dung (dried to 20% of fresh weight)	133	266	530
Anaerobically digested cattle dung sludge (wet)	676	1,350	2,700
Anaerobically digested cattle dung sludge (dried to 10% of wet weight)	80	160	320

The nitrogen present in inorganic fertilizers is assumed to be potentially 100% available to plant=. For comparative purposes, the availability of nitrogen in organic manures i" assumed to range from 25% (e.g. Idnani and Varadarajan 1974) to 100%. Both inorganic fertilizers and organic manures often contain plant nutrients in addition to nitrogen, and organic manures provide important soil conditioning factors. Although important for sustained maintenance of soil fertility and plant growth, these are not presented in this Table, for the sake of simplicity. Nitrogen values of manures are based on Rajabapaiah et al. 1979.

The application of digested sludge over a period of years has led to a continuous increase in crop production (Marchaim 1983 and others). This may be due to the effect of slow release nitrogen compounds and improved soil structure. In order to utilize low grade phosphorite, a new type of fertilizer - biogas sludge phosphohumate - has been developed in China. This is made by mixing the sludge with phosphorite powder in ratios of 10:1 to 20:1, and comporting for 1 - 3 months. In soils lacking phosphorus the use of this material may increase yields by over 20%.

Typical compositions of manures after anaerobic digestion are shown in Table 9.6. Note that the three fertilizer elements, nitrogen, phosphorus and potassium, are each present in the range of 1 - 1.5%.

Algae production

Digester effluent has been added to a number of experimental ponds to evaluate its effect on algae production. In Taiwan, Hong et al. (1979 grew the blue-green algae Spirulina platensis in the effluent from a swine manure digester. The algae were harvested from the surface with nets, and productions of 7.3 and 9.7 g/m3 (equivalent to 1.9 x 2.5 tonnes/ha/year) were achieved during winter and summer respectively. The harvested algae contained 57.5% protein.

Table 9.6: Chemical Composition of Organic Digested Manures (oven Dry Basis)

	N	P	K	Fe	Mn	Zn	Cu
	%	%	%	ppm	ppm	ppm	ppm
Liquid slurry	1.45	1.10	1.10	4000	500	150	52
Sun dried slurry	1.60	1.40	1.20	4200	550	150	52
Farmyard manure	1.22	0.62	0.80	3700	490	100	45
Compost	1.30	1.00	1.00	4000	530	120	50

Filtering, collection and drying of unicellular algae is costly and requires large areas of land and volumes of water. The addition of chemical coagulants, such as alum, increases costs and reduces the acceptability of the dried protein as an animal feed. Boersma et al. (1981) concluded that the production of algae from digested swine manure was not the best use of the slurry. Maramba (1978) point out that soybean oil meal is a less expensive protein source. This does not take into account the potential of algae as a source of phycochemicals.

The use of anaerobic fermentation treatment in livestock breeding

There are many nutrients in anaerobically digested manure and it can be used not only for raising the fertility of soil, improving soil, increases agricultural production, for feeding fish, finless eel, earthworm and pigs, but can also be used for breeding silkworm and hatching chickens. The use of Anaerobic fermentation treatment in breeding is a comprehensive utilization of both the biogas and the slurry. Many farmers in the villages of China have successfully made use of biogas technology (Fang Xing and Xu Yiz Hong 1988) in breeding silkworms with biogas, since this requires suitable heating and lighting. Lighting with biogas lamps enables the cocoons to be formed 4 - 6 days earlier, the quality of cocoons is good, and the output is increased by about 30% over that without using biogas lamps in otherwise the same conditions.

Nutritional value of effluent in livestock diets

Considerable interest and effort have been directed towards the use of animal wastes as fodder. The results of early experiments were reviewed by Smith and Wheeler (1979), and suggested that manure could be reefed with some nutritional benefit, and with little adverse effect on animal health or the wholesomeness of animal food products.

Many studies have been performed to evaluate the chemical composition of biomass resulting from thermophilic anaerobic fermentation of cattle wastes (Prior and Hashimoto 1981, Marchaim et al. 1981). Because of high capital costs involved in building the fermentation plant, preliminary analyses showed that a reasonable return for the feeding value of the effluent biomass is essential to the profitability of the fermentation process (Hashimoto and Chen 1981). While research has shown that biosolids have nutritional value for beef cattle fodder, the supporting data regarding the quantity and quality of protein, fibre, ash and energy are subject to a wide range of interpretations.

Total ash and total nitrogen (N) in the influent and effluent do not change significantly during fermentation. However, the proportion of total N that is in the form of ammonia- N increases from $\approx$ 27% to $\approx$ 48% (Prior and Hashimoto 1981). Assuming that all the non-ammonia-N is in the form of protein, the protein content is enriched from $\approx$ 25% - $\approx$ 32% (dry matter basis) during the fermentation process, on the basis of amino acid composition of the influent and effluent. The amino acid content of the dry matter is approximately doubled. Thus, the fermentation process enriches the protein content of the dry matter. If all the N in the effluent could be recovered and used as a diet supplement, the latter would have a high crude protein equivalent; however, making all the N in the effluent available is difficult, due to the finely divided bacterial cell size and the solubility of ammonia-N.

Normally, when effluent is centrifuged, over half the amino acid-N is lost in the centrate. This probably represents bacterial protein (intact cells, etc.), which would be a more digestible amino acid fraction than amino acids that may be trapped in the more lignified biosolids captured during solid/liquid separation. In centrifugation and belt filtration, most of the ammonia-N is lost in the liquid waste. Ammonia-N in the effluent represents $\approx$ 48% of the total N. This level of ammonia in the effluent should not present a problem as an N supplement in ruminant rations.

Re-feeding of digested animal wastes to cattle, pigs and poultry has been demonstrated to be a potential use of the effluent product. When organic materials are digested anaerobically, a significant fraction is reduced to ammonia, some of which is taken up by growing bacterial biomass and converted to new amino acids. With cattle waste, increases of 230% of total amino acids have been measured after digestion (Table 9.7). In addition, considerable quantities of vitamin B12 are synthesized during digestion, and preliminary results from work at Maya Farms (Maramba 1978) indicate concentrations of over 3,000 mg B12 per kg dry sludge. In comparison, the main sources of B12 in animal feeds, fish and bone meal, contain 200 and 100 mg/kg respectively. Digested sludge thus has potential as an animal feed supplement and, due to the high costs of these supplements ($200/ MT for cottonseed meal), could enhance the financial viability of biogas plants.

Table 9.7: Comparison of Amino Acid Composition of Cattle Wastes, Dried Centrifuged Fermenter Biomass, Fermenter Influent and Fermenter Effluent Cattle Centrifuged Fermenter Fermenter

Item	Cattle waste	Centrifuged biomass	Fermenter Influent	Fermenter effluent
Aspartic acid	9.3	12.3	12.7	24.8
Glutamic acid	18.4	20.9	24.6	45.4
Alanine	13.1	8.2	20.7	16.3
Glycine	6.2	7.6	15.2	13.8
Serine	3.7	4.3	4.8	8.3
Proline	5.6	6.9	6.7	11.4
Tyrosine	3.2	2.8	3.3	7.9
Phenylalanine	5.0	5.3	6.2	12.6
Threonine	4.3	5.7	6.2	10.9
Methionine	3.3	1.5	2.6	4.9
Valine	6.1	6.8	7.6	15.3
Leucine	8.9	11.0	11.1	21.2
Isoleucine	5.0	6.2	6.3	13.7
Lysine	5.4	6.2	7.7	14.8
Histidine	1.7	2.4	2.7	4.4
Arginine	2.7	5.3	4.4	9.6
Total amino acids	102.0	113.4	142.8	235.3

Note: Data, expressed as mg amino acids per g DM, obtained following 72 hours of acid hydrolysis in evacuated flasks. Values represent mean of three determinations on composite material during two separate weeks.

Reference: Prior and Hashimoto (1981).

At Maya Farms in the Philippines (Judan 1981), solids are recovered in settling tanks and dried in the sun. The feed material from the sludge provides 10 - 15% of the total feed requirement of pigs and cattle, and 50% for ducks. At this concentration, it was found that weight gains for pigs were slightly higher than a control group (Maramba 1978). Alviar et al. (1980) also found that dried sludge could be substituted in cattle feed with satisfactory weight gains and savings of 50% in the feed concentrate used. The apparent gross energy of the dry matter does not significantly differ between influent and effluent, but available energy is lower in the effluent. Volatile fatty acids serve as primary sources of energy for the ruminant: they decrease from 9 - 10% to 3 - 4% during anaerobic fermentation. This is because the process converts available energy into gas. Hence, the effluent, apart from the bacterial debris, has a low feed value for energy, though retaining its value as a roughage source to stimulate rumination.

The mineral content of the dry matter also remains constant during the process of fermentation, but the concentration is increased, due to the loss of dry matter during the process. Factors that influence the mineral

content of the waste are the type of installation from which the wastes are obtained and the amount of supplementary minerals added to the diet. Of particular interest is the high ash content of the dried centrifuge cake and the corresponding high silica content. Silica ($SiSO_4$) is an important factor in digestibility, particularly of the cell wall constituents of more mature forages. Plant metabolic silica causes an average decline of 3 units in digestibility per unit of silica. When there is sand or soil contamination, a factor of 1.4 units decline in digestibility per unit of silica is applicable. It is likely that silica in the fermenter effluent results, to a large extent, from solid contamination, particularly in wastes derived from dirt lots.

It was found by Prior et al. (1981) that the use of fermenter biomass a" a feed ingredient for livestock appears to have merit, although some technical problems must be solved. Dried, centrifuged biomass can be fed at a level up to 10% of dietary dry matter, without markedly affecting the utilization of diet components. The disadvantages of feeding it are that considerable quantities of nutrient are lost by centrifugation, while the capital and energy costs of installation and operation of centrifuge and drying systems are extremely high. While elimination of the drying process would retain additional N. storage of the wet centrifuged biomass would be a problem, particularly during extreme weather. The incorporation of the total fermenter effluent into a ration has the advantage of retaining a higher proportion of the nutrients, but the amount of water in the effluent limits the quantity that can be incorporated into the ration. The major effects that have been observed from feeding the effluent have been an apparent decrease in the digestibility of dry matter, N. ash and gross energy (in sheep) and decreased total ruminal volatile fatty acid concentration in cattle (Prior et al. 1981).

Feeding trials have also been conducted by Pacific Gas and Electric and Southern California Gas Companies (1981). Their biogas pilot facility, near Brawley, California, provided a supply of effluent, and feeding trials were conducted at El Centro, California. They found that there was no apparent reduction in ration palatability and consumption by cattle, but at 10 - 12% of the ration, centrifuged additions to it had a very pronounced effect on cattle performance. In both the research and the feedlot trials, feed consumption increased, rate of gain decreased, feed conversion rate decreased, and the cattle did not exhibit the degree of finish at slaughter of cattle not consuming biosolids. At this rate of feeding, the biosolids appear to be a negative energy input, requiring energy from the digestive system to pass the material through. At this feed intake rate, there wan still expected to be a nutrient contribution from mineral- and nitrogen containing ingredients (both protein and non-protein nitrogen). The high ash component imposed the principal penalty to the biosolid, since it diluted the energy in the ration, and required additional energy to pass the silica (from plant silica and soil) through the gut.

Because of the low efficiencies and the high capital and operational costs associated with centrifuging (Hashimoto and Chen 1981), other methods to recover the nutrients in the biomass were investigated. Studies were undertaken, in which the effluent was mixed directly with corn and roughage source. The advantages of this are the use of 100% effluent and the retention of the ammonia in the diet. The disadvantage is a high dietary moisture, which can reduce "bunk life" and consumption. While Prior and Hashimoto (1981) found negative effects on consumption, Marchaim et al. (1981), when using "NEFAH" process effluent, which is of much higher solid content (up to 12%), found that 25% of the total dry matter in the diet of Holstein heifers can be replaced, while retaining normal performance (Marchaim 1983). Experiments with feeding calves were continued in Israel, and showed a saving of 20 - 30% (ibid.). This could be done only when a cheap source of metabolic energy is used (e.g. grain dust): when corn or grains have to supply the missing energy, the saving is lower. This was more pronounced when beef cattle were fed up to 25% dry matter of digested slurry, and gained a little less weight (ibid.). The main reason for that is probably the adaptation period of the cattle to the diet, influencing performance.

On the other hand, it was found that one year after stopping feeding the calves with effluent, the 30 calves fed on slurry for over 14 months produced significantly more milk than the 30 calves of the control. This was observed in the first two lactating periods: no explanation for the phenomenon was offered.

To solve the main problem, the deficiency of metabolic energy in the effluent, an attempt was made to regenerate the energy by photosynthesis on the separated fibre fraction, the "Cabutz".

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Fish feeding with digested cow manure

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When digester slurry is used in ponds, the nutrients stimulate the growth of both phytoplankton (algae) and zooplankton (daphnia and crustaceans), which the fish harvest. Alviar et al. (1980) investigated the growth of fish in an integrated farming scheme in the Philippines. The average yield of Tilapia nilotica was 25 kg/m^2 every two months (19 tonnes/ha/year).

In southern China, cultivation of fish in ponds is common. Normally the fish are fed wheat bran pellets. In recent years digester slurry has been used as a feed supplement, increasing fish production and decreasing costs for feed (National Office for Biogas, 1982).

The use of untreated manure for feeding fish has been a common usage in the Far East for many years. The use of cow manure for the enrichment of fish ponds, however, is relatively uncommon (Hepher and Schroeder 1977). This is because cows are allowed to roam freely, while pigs and poultry, which are raised in larger numbers than cows, are kept in feedlots associated with the ponds, and their manure is utilized for feed in the ponds. Studies on the use of organic fertilizer in aquiculture have been undertaken in Israel (Moav et al. 1977; Rappaport and Sarig 1978) and the United States (Buck et al. 1978). The effect of liquid manure on growth in polyculture of several varieties of fish was studied in Israel by Moav et al. (1977).

Anaerobically digested cow manure (mesophyllic) was used as feed in fish ponds in 1976 (Schroeder et al. 1976; Marchaim and Criden 1981). These experiments were conducted in polyculture, with common carp, tilapia and silver carp. The ponds were divided into 3 groups, according to differences in treatment: the first group was fed pellets; the second group, liquid cow manure; and the third, digested cow manure. The tilapia grew at the same rate in all three groups, but the carp fed on pellets grew faster than the other two groups. The researchers were unable to determine the effect on the manure on each species in this experiment, though it did indicate that tilapia is probably one of the species best suited to feeding on slurry.

Dissolved oxygen was also measured in the early morning hours, and varied between 1 - 8 ppm, remaining at over 3 ppm for 80% of the time. No correlation was found between feed treatment and dissolved oxygen. Primary production studies were conducted to estimate the effects of organic materials on fish yield. Rates of photosynthesis were found to be only slightly higher in slurry- fed ponds than in chemically fertilized ponds. In ponds fed with slurry plus feed, a higher proportion of zooplankton was found in the total plankton population than in non-manured ponds.

As a result of the three seasons of experiments, it was felt that digested slurry can be used in fish ponds, thereby saving 50% of pellets used, with a considerable influence on fish pond economics. Several other experiments have been conducted by the "NEFAH" group at kibbutz fish ponds, using different slurries and diet compositions. In the Migal Laboratories, growth rates of tilapia were examined with (a) high protein pellet diet (28%); (b) 50% low protein pellets (21%) + 50% wet untreated effluent; (c) 50% low protein pellets + 50% sun-dried effluent (dry matter basis) by Degani et al. (1982).

The results of this study show that digested slurry can replace 50% of the food in fish ponds, but that the different kinds of slurry are not equal in their effects. In a study of the influence of the liquid fraction of the digested slurry on tilapia culture, it was found that the low level of carbohydrates was replaced by growing algae, to balance the ratio of metabolic energy to protein in the diet. It was found that the liquid fraction of the slurry may be important in improving the oxygen level, raising primary production and the concentration of chlorophyll a.

Marchaim et al. (1983) showed that in fish ponds, substituting 25% of the food with cow manure gives the same production

from the pond as regular feed. The level of oxygen is higher in the ponds fed with slurry than in control ponds fed with regular feed. In intensive growth ponds (22,000 - 30,000 fish/ha of 350 g fish) growth rates of carp were much higher in ponds fed with a 30% substitution of feed by the liquid fraction after sieving through a vibrating screen, than in control ponds.

Fang Xing and Xu Yiz Hong (1988) found that the big-manure, when put in the fish pond, can be used to breed plankton in the water for feeding fish, achieving good results. The Chinese way of doing it is to spread the slurry into the fish pond at 400 kg per mu every three days. Under this management the breeding of fish with big-manure is best. It gives five benefits:

(1) There are many nutrients in biogas manure. It can breed plankton in water for fish nourishment;
(2) It has been fermented completely, and therefore it can not consume more dissolved oxygen and does not reduce the quality of the water;
(3) It change the colour of water into a drab tea-colour, contributing to absorption of heat from the sun. The temperature of water is raised, and contributes to the fish growth;
(4) After anaerobic fermentation, bacteria and eggs of parasites in the big-manure have been killed: it therefore reduces fish diseases;
(5) The pH of big-manure is neutral, improving fish growth.

Effluent as a substrate for growing plants and crops

Uses for horticulture
Growth and rooting experiments

It is widely accepted that an improved growth medium for horticulture and mushroom production is obtained when organic materials are included. The most common organic component is peat moss (Chen et al. 1984) which may also serve as the sole component of growth medium. The use of peat is, however, accompanied by some problems:

(1) The price of horticultural peat is high, and shipping it long distances considerably increases its price;
(2) Peat resources throughout the world are limited and nonrenewable (ibid.);
(3) In some cases, sterilized peat serves as an enrichment medium for various phytopathogenic fungi species, such as Pitum sp. It seems, therefore, that finding substitutes for peat is an important task for soil scientists and horticulturists.

Liquid digested slurry was found to be an unsuitable growth medium, completely inhibiting the germination of seeds. Experiments were therefore conducted with thermophilic effluent, after sieving through a vibrating screen and using the coarse fibre fraction (called "Cabutz"), after leaching the water to reduce salinity.

Raviv et al. (1983) testing herb plants on 5 different media, for development and regenerative ability under outdoor conditions, found that Cabutz gave better results than peat-moss or rock wool. Similar results were obtained with most (but not all) house-plants, and Cabutz is now sold as a substitute for peat- moss to many commercial greenhouses and plant nurseries in Israel.

Table 9.8: Physical comparison of "Cabutz" and other substrates

Type	Volume wt. g/cm^3	Pore volume % volume	Air capacity % volume	Water capacity % volume	Exchange capacity meq/100 g
Cabutz	0.12				
	0.08 - 0.17	86 - 95	32 - 50	45 - 60	112
Sphagnum	0.07				
Peat	0.04 - 0.085	95 - 97	15 - 40	55 - 82	100 - 140
Amorphous	0.16				
Black Peat	0.13 - 0.18	88 - 92	7 - 12	76 - 85	110 - 160
Coarse Sand	1.26	51	25	26	0 - 2
Silt	1.09	58	18	40	2 - 6
Heavy Clay	1.01	61	19	42	80 - 100

The chemical compositions of Cabutz and enriched Finland peat are also similar, though Cabutz is not as stable as peat, and chemical changes occur during storage.

Sieved, dried effluent from thermophilic digestion in the Kaplan Industries plant in Florida (built by Hamilton Standard, Inc. of Connecticut) is also sold as soil conditioner to nurseries (Coe and Davenport 1981).

The intensive work done on thermophilic digested slurry has given rise to the suggestion that some special characteristic is gained during fermentation at 55°C. This is being examined by the Volcani Institute, Israel. One of the results of growing crops on Cabutz was a faster growth of the root system than on other substrates; and Cabutz also had a positive effect on the growth rates of corn and wheat. Raviv et al. (1982) examined the possibility of achieving higher yields of crops on Cabutz, on the basis of ideas mentioned above ("Fish feeding with digested cow manure"). The purpose was to harvest the foliage after a short period, for direct feeding or silage. The possibility of resowing on the same substrate was also examined. In spite of a relatively low percentage of germination, it appeared that, after the period of germination, an increase of approximately 80 g/m /day in weight was achieved in the foliage alone. To this, the high rate of root growth has also to be added, probably the main contributing factor to the high growth rate. After 4 seasons of growing corn on the same Cabutz, winter wheat was also grown on it. It was estimated that 10 - 20 kg/m dry matter could be grown in one year, but this very high yield has yet to be confirmed in field experience. It is also noteworthy that the liquid fraction can be used as a fertilizer, and that the quantity of water needed per ton of dry weight was considerable less, though the irrigation program had to be carefully controlled.

The amount of pesticides and herbicides required was also very small, since most of the pests and herbs are destroyed by thermophilic digestion (see below). This phenomenon is of special importance in mushroom cultivation. Results from Migal Laboratories in Israel (Levanon et al. 1983) showed an increase of almost 20% in yields of mushrooms grown on Cabutz, instead of casing soil, with an acceleration of growth in the first 3 cuttings.

Uses for horticulture

Chen et al. (1984) have described the main physical and chemical properties of Cabutz, as compared to sphagnum peat-moss. The similarity in major physical properties is Striking: The bulk density of Cabutz ranges from 0.08 - 0.12 g/cm^3 compared to 0.09 g/cm^3 for peat; particle density is the same (1.6 g/cm^3); the porosity for Cabutz was calculated to be 93 -

95% compared with 95 - 97% for peat-moss; the hydraulic conductivity value for Cabutz and peat is 120 - 150 cm/in and 150 cm/in, respectively. However, a significant difference in the water/air ratio should be noted. One of the most important requirements of a growth substrate is its ability to hold and supply large quantities of water, while at the same time it should be structurally adapted to entrap large volumes of air. The minimum air space in peat should be around 15% of volume, while the ideal value is around 20-30%. When saturated Cabutz was allowed to drain for two hours, the air space was found to be 32%, while in peat moss it reached about 18%. After 24 hours of drainage, the air space was 43% and 24%, respectively. Cabutz is well aerated, because of its comparatively large particles. As a result, it also requires more frequent irrigation.

The chemical properties of Cabutz are close to those of enriched sphagnum peat, although generally higher values for N. P. K were observed in Cabutz. Experiments with sensitive plants grown on Cabutz have shown response to fertilization with iron chelates (Raviv et al. 1983).

Growth and rooting experiments

Trials on growing cucumbers in different Peatrum treatments were conducted in a nursery in Israel. The control consisted of the standard growth medium consisting of 50% sphagnum peat moss (either Finnish or Dutch) and 50% perlite no. 4 or fine tuff (0 - 8 mm). The experimental substrates, after 3 h of leaching, replaced the peat-moss. Each replicate consist of 48 seeds. The experiment was designed in randomized six blocks. Irrigation by spraying was applied for 30 sees each hour. Plants were fertilized, from the sprouting stage, with 3 1 Sheffer 737 (Israel Chemicals, Ltd.: mixture of 7.3% N. 3.2% P_2O_5, 6.5% K_2O and micro-elements) to a tray daily. 20 days after sowing, plants were harvested and dried at 65°C for a week.

In the comparison of Peatrum (the slurry of digested rumen content) with Cabutz and peat-moss for growing cucumbers, rooting rates were initially similar, but the growth-rate of plants in Peatrum was slower, and there was a clear lack of balance in the nutrient supply. The beneficial effect of organic materials as a component in rooting media can be partly explained by the presence of root-promoting materials in the products of decomposition, and of humic acid compounds. These materials are more abundant in peat moss and Cabutz than in Peatrum, which may explain the lower growth-rate in the latter. Composting probably generates some of these compounds, and a suitable nutrient supply (iron) must be added. Peat-moss has a higher fibre content than Cabutz, and the higher the fibre content, the longer the period of comporting required.

The use of composted and uncomposted Peatrum as a growth medium for seedlings and plants in greenhouses showed that it is of lower quality than Cabutz, but this could be the result of not adequate composting and of some deficiencies in oxygen and nitrogen.

Uses of effluent for mushroom production

Standard chemical and physical methods were defined by Levanon et al. (1984) for the analysis of substrates for mushroom production. These parameters were set according to the local conditions in Israel, and they enabled the development of a quality control system for the production of substrates for mushrooms.

Most of the substrates for mushroom production are organic wastes or by-products. Agricultural by-products, as well as industrial and municipal wastes, are used, mainly via composting, to produce raw materials for mushroom production. There is a need for standard chemical and physical parameters that will allow production of the proper substrate for each

mushroom variety in every country, with local wastes or by-products. Of supreme importance is the knowledge of the nutritional needs of every mushroom variety. In the present study, standard chemical and physical methods were defined for the analysis of substrates for mushroom cultivation. The use of these methods allows manipulation of the substrate composition, according to the needs of the growing fungi in important stages of its life cycle. These parameters enable the development of quality control systems, for the production of proper substrates for mushroom cultivation.

Chemical and physical parameters for qualification of substrates (composts and casing material) for mushroom production were selected after a series of experiments. Those of critical importance in various stages of substrate preparation and mushroom growth are: moisture, ash, organic matter, total and ammonia N. crude protein, lignin, cellulose and hemicellulose. Physical parameters are essential, especially in the qualification of substrates for casing soils, because their main role is to provide the proper physical conditions for fruit bodies development. The most important parameters are: electrical conductivity, volume weight, specific density, porosity and water holding capacity.

An investigation was conducted on the suitability of Cabutz as a casing soil in the production of mushrooms (Agaricus bisporus). In recent years, peat moss has been used as the main component of the casing material. The casing material has to fit the following requirements:

a) Sufficient water holding capacity to serve as a water reservoir for the growing mushroom crop;
b) good structure - porosity, to maintain gas exchange between the compost surface and the growing rooms air;
c) pH values in commercial casing are usually 7.3 - 7.8;
d) the presence of soluble ions (electrical conductivity) must be low;
e) the casing must also be clean of soil pests and pathogens, therefore pasteurization (heat or chemical treatment) is usually needed.

There is some association between microflora and mushroom mycelium which supports its transition to formation of fruit bodies. Hence, pasteurization must be limited to avoid elimination of beneficial micro-organisms (Hayes 1978; Levanon et al. 1983, 1984). As in horticulture, a shortage of peat moss has led to a continuing search for alternative raw materials which could serve as casing soil. In order to check if Cabutz could serve as a raw material for casing soil, its chemical and physical properties were compared with those of peat moss (Table 9.9), with similar results to the experiments described above. There is a great similarity in the physical properties (specific density, volume weight, water holding capacity and porosity) between peat moss and Cabutz, although the water holding capacity per volume, calculated on a saturated matter basis, is higher in Cabutz. Despite its high water holding capacity, the physical structure of Cabutz (especially its high porosity) allows the high rate of aeration required for mycelium growth and fruit bodies development.

Table 9.9: Chemical and Physical Properties of Cabutz and Sphagnum Peatmoss

Parameter	Cabutz	Peat Moss
Electrical conductivity (mS/cm*)	1.2 - 1.4	1.3 - 1.7
pH*	8.1 - 8.3	3.3 -3.7
Ash %	12.0 - 14.0	4.0 - 4.5
Total Nitrogen (%)	1.9 - 2.1	0.4 -0.6
Ether-soluble fraction (%)	0.7 - 0.9	0.5 - 0.6
Phosphorus (%)	0.7 - 0.8	0.02- 0.03
Cellulose (%)	27.0 - 30.0	42.0 - 45.0
Lignin (%)	28.0 - 30.0	16.0 - 18.0

Specific density (g/ml)	1.23 - 1.27	1.0 - 1.16
Volume weight (g/ml)	0.10 - 0.11	0.05 - 0.06
Porosity (v/v) (%)	91.0 - 92.0	95.0 - 96.0
Water holding capacity at saturation (w/w) (%)	900.0 - 910.0	910.0 - 930.0
Water holding capacity at saturation (g/ml) (%)	90.0 - 96.0	67.0 - 75.0

*Measured on a wet matter basis - other parameters measured on a dry matter basis.

The chemical composition of Cabutz differs from that of peat moss in several parameters. In Cabutz, higher pH, nitrogen and phosphorus content were found. The pH of the Cabutz (8.3 - 8.1) is close to the optimal value for easing soil, which makes the usual supplementation of peat moss with limestone (in order to raise pH value) unnecessary. On a recent commercial-scale trial, we found a high yield (22.0 ± kg mushrooms/m) with Cabutz as a casing layer. As a waste material product, the price of Cabutz (which is produced commercially) is constantly lower than imported peat moss. The benefits of using Cabutz commercially are therefore both ecological (recycling agricultural waste with pollution potential) and economic.

Fig 9.1: Cumulative mushroom yield in a commercial farm using 17 square meters for each treatment in which Cabutz, Peatrum and comporsted Peatrum were used as easing soil. Only one experiment was performed because of the limitations of commercial conditions.

It was shown by Levanon et al. (1983, 1984) that mushroom yields, using Cabutz as casing soil, reached those in the standard uses of peat-moss, with some higher yields in the first two flushes of mushroom growth. It was also found that the Cabutz contains less harmful moulds than peat-moss. The laboratory experiments were then scaled up to a commercial mushroom farm and high yields (2.5 kg mushroom/m^2) with leached Cabutz as casing soil were achieved. The price benefit of using Cabutz is high, and is now in widespread use in northern Israel mushroom farms (Marchaim 1991).

Mushrooms were grown in commercial rooms with automatic climate control (temperature and humidity) with the addition of forced fresh air circulation, and control of carbon dioxide concentrations by means of Siemens IR CO_2 detectors). Each room contained a total effective growing area of 170 m^2 , in two rows of five beds of 17 m^2 each, one on top of the other. The experiment was performed in 3 beds of 17 m^2 each, with fresh or comporsed Peatrum for 2 months and a control of 50% peat moss with 50% Cabutz, the standard mixture used on farms. The beds were filled with compost' according to the commercially accepted ratio of 115 Kg compost/m^2 . Compost was obtained from a commercial plant nearby. The casing materials were treated with formaldehyde, the disinfectant commonly used on farms (0.5 l formaldehyde (40%) in 15 l of water for each m^3 of casing material.) Fresh Peatrum was compared to composted Peatrum and to the control substrate. The Peatrum was additionally washed with water to a conductivity of less than 4 mmohos and limestone was added according to local procedures. All environmental treatments were performed as for Cabutz/peat treatment.

The results of using Peatrum as a casing soil for mushroom production were encouraging in comparison to Cabutz and peat-moss (Fig. 9.1). The comported material showed a better performance as casing soil, but the environmental conditions for using "Peatrum" have yet to be established. Peatrum was also examined, fresh and after 2 months of composting, as a substitute to Cabutz. Peatrum was used as 100% casing soil, while the control was 50% peat + 50% Cabutz. Cabutz is probably richer in suitable nutrients, and effects on the morphogenesis of the fungus were better than in high straw content Peatrum (Levanon 1988).

Fresh Peatrum has lower quality than Cabutz as a casing soil and growth medium, but reaches almost the same quality after 2 months of composting.

At the same time, it is possible to adapt conditions to use Peatrum as a casing material, without loss of quality.

Composting processes

Several ways of treating the slurry were examined by different groups, one of them separation on a vibrating screen, as described by Marchaim (1983), and washed with water. The liquid phase is usually used as a liquid fertilizer for irrigation, or is discharged.

In the anaerobic digestion treatment of slaughterhouse wastes, the sieved fibrous material, the Peatrum, is the result of the above process, and was used almost immediately (Marchaim 1991). The Peatrum was mixed with a shovel every 2 - 3 days to accelerate comporting, by exposing it to as much air as possible. Samples were taken for analysis and growth experiments during the composting process

Fig. 9.2: Changes in organic matter and ash content in the Peatrum from a slaughterhouse after thermophilic digestion, with composting time (from Marchaim 1991).

Composting is an exothermic, aerobic, microbial process of stabilization of organic material in heaps. The microorganisms in this process derive from the atmosphere, water and soil; it is an indigenous mixed population. The organisms belong to the microflora (bacteria, actinomycetes, fungi, algae) and microfauna (protozoa). Controlled environmental factors are the requirement for microbial metabolism, and the function of the process technique for composting is to optimize and to maintain these factors. The most important environmental factors are water, oxygen, nutrients, pH level, temperature.

Water: Microbial metabolism needs free water. Therefore, theoretically the optimal moisture content of the organic material is 100%, which excludes water lack during the composting process. In the three phase system (solid, liquid, gaseous) the part of the pores filled with gas and their permeability and communication to the atmosphere must be at a level to allow the exchange of the respiration gases.

Oxygen: Because aerobic microorganisms are responsible for the composting process, their oxygen demand has to be supplied by atmospheric air. At the same time, the carbon dioxide of the microbial respiration must be removed. For this, the minimum of the oxygen content and the maximum of the carbon dioxide content should be about 10%. The oxygen demand depends on the temperature: the maximum is between $50°$ - $60°C$.

Nutrients: For the metabolism of the microorganisms, water, oxygen, a carbon source (the organic material), macro-nutrients (nitrogen, phosphorus, potassium) and certain trace elements are necessary in water soluble form. Special requirements belong to the C/N ratio and the availability of the carbon. Because the C/N ratio of the microbial substance is between 4 - 9, the C/N ratio of the organic material should be no higher than 20 - 25, and for a spontaneous start of the composting process no higher than 15. If the C/N ratio is wider, there will be also biodegradation and microbial growth, but retarded by nitrogen lack. If the C/N ratio is lower, the microbial development is undisturbed, but the losses of nitrogen as gaseous ammonia are relatively high, because the microorganisms cannot use it rapidly. The availability of the carbon of plant material is specially influenced by the degree of lignification.

Temperature: During composting the microbial metabolism release heat (34 to 42 kJ/g C), which results in a heat accumulation in large heaps due to the insulating effect of the material. The temperature can rise up to over $80°C$. Depending on the temperature, different groups of microorganisms are active. Because the highest rate of degradation is achieved by thermophilic microorganisms, at a temperature between $50°$ - $60°C$, this temperature is the optimum for a quick composting process. From the viewpoint of safe hygienization, the temperature should be higher than $60°C$.

pH-level: The optimum of the pH-level for bacteria is in the neutral to alkaline range, for fungi in the acid range, and for actinomycetes between both. In general, a pH-level of 7 is required, but decomposition is possible at a pH-level of 3 - 9 of the substrate. The microorganisms are able to change the pH-level by their metabolism to an optimal range, but they can also change the pH-level to a toxic range.

There are only few reports about composting of separated solid matter. Two examples can show the composting behaviour of characteristic substrates. The first example demonstrates the composting of solid matter from liquid manure (Terre et al. 1987; Raviv et al. 1987). The solid matter had a crumbly structure and an air volume of 44% for the fresh manure, compared with 39% for the thermophilic digested manure, and 31% for the two-stage fermented manure. The temperatures during the self-heating process were high enough to kill pathogenic organisms and weed seeds. The product from this composting process is commercially marketed in Israel, and is the Cabutz, referred to above.

The second example shows the problems when composting separated solid matter. The substrate from thick stillage and grass silage, separated after hydrolysis, was crumbly but smeary with fine fibres of the grass. At the start of the composting process, the smell of the substrate was distasteful because of the fatty acids (pH 5.3). Although the pH value was low, the temperature rose up to 71°C within 5 days. When the substrate was turned after 6 days it had lost the distasteful acid smell. During the following weeks of composting the substrate became softer and softer, and lost the air volume, so that anaerobic conditions predominated.

Process alternatives for composting

The process alternatives for the composting of separated solid matter depend primarily on its water content, consistency and structure. For composting in windrows higher than 0.5 m the total solid content should be at least 25% and the air volume should be at least 30%, or better 50%, to provide aerobic conditions. At this air volume, self-aeration of the fine-crumbly or fine-fibrous substrate is possible, up to a height of 1.0 - 1.5 m. For a composting process in boxes, with a filling height above 1.5 m, aeration is necessary. If the total solid content is higher than 25%, and the air volume more than 30%, the solid matter is suitable for direct composting in windrows, with heights up to 1.0 - 1.5 m; If the total solid content is between 15 - 25% the air volume is often lower than 30%, and aeration insufficient, even though the substrate has a crumbly structure. A composting process in windrows without additives is possible when the height is less than 0.5 m and the substrate is mixed from time to time, to keep or to produce air pores; When the total solid content of the solid matter is 15 25%, and the consistency pasty, viscous or crumbly, an addition of water- absorbing and structure-forming stuffs is necessary (e.g. straw, wood chips, sawdust); At total solid contents lower than 15%, the solid matter has a pasty or liquid consistency and an addition of dry matter is essential; At low total solid contents of the solid matter, chopping of the straw allows quick absorption of the water.

Is the composting profitable?

The costs for separating out the solid matter from biogas plants are composed of a separator, a tractor shovel or tractor with frontloader and a passable bed-rock for the storage of the solid matter. These costs arise in all processes, with separation of solid matter as an essential part of the process. If the aim of the separation is the production of compost material, additional costs for the composting process result from a windrow turning machine (self-powered or tractor-powered), a passable surface for the windrows, and a roof for rain-protection for composting during the whole year. If the contents of total solids of the separated solid matter are too low for the composting process additional investments are necessary for chopping or crushing of water absorbing dry matter, storage of the dry matter, and a tractor with a trailer for the transport of the dry matter to the windrows. If the consistency of the solid matter is liquid or pasty, so that a mixing of the components with the

turning machine is impossible, a mixer-dosing device for the solid matter and the dry matter is required. If the intention is to sell the compost in plastic bags, investment is necessary for a dryer for compost, or storage of water-absorbing additives (e.g. Perlite or peat), sacking equipment and storage of the bags.

The content of total solids after the composting process is in the range of 55 - 70%, too high for storage and transport in plastic bags without trouble with surplus liquid. The content of total solids should be less than 50%.

Composting of separated solid matter for utilization in horticulture or in hobby gardens offers a high return for compost production. The allowable limit of costs depends on the price of the compost at the market. Examples from Israeli practice show satisfactory profits for selling high-value composts (free of pathogenic organisms and weed seeds, smelling of earth, crumbly, favourable to growth of plants). However, compost production of some thousand m^3 per year seems to be necessary, because of the high investment. Composting of separated solid matter for utilization in agriculture as fertilizers seems not to be viable, because of the high costs, and the alternative possibility of utilization without comporting. If a comporting process is necessary under for environment protection, or degradation of odoriferous components of the solid matter after hydrolysis (fatty acids), storage in heaps, with a maximum height of 0.5 m, is possible.

Composition and digestibility of different sized fractions in cattle slurry

Animal slurries may be passed through a separator, a common item of farm machinery, to give a liquid fraction which is more easily pumped. This separated liquid gives fewer problems of blockage and scum formation in subsequent anaerobic digestion, and may also be capable of digestion in anaerobic filters (Peck and Hawkes 1987). Higher gas yields have been reported from the digestion of separated cattle slurry when compared with whole cattle slurry (Rorick et al. 1984; Lo et al. 1983, Peck et al. 1985). Peck et al. (1989) showed that passage of whole cattle slurry through a commercial roller press separator alters the composition of the waste as well as its size distribution. The composition and digestibility of fractions of various sizes obtained from whole cattle slurry have been compared. The smallest particles have a higher lignin: holocellulose ratio, produce gas richer in methane, and give lower gas yields per volatile solids added. A reduction in particle size after digestion was observed in all fractions, with the >1700 µm fraction least affected.

It was found (Peck et al. 1988) that the biogas from the smallest fractions was richer in methane. This is presumably related to the different composition of the solids destroyed, since lipids and proteins should give a higher percentage of methane than carbohydrates. After digestion, the digester contents were again sieved, and a reduction in particle size was observed in all fractions. The >1700 µm fraction was least affected, only 22% of the particles by weight being smaller after digestion, while in the remaining fractions 31 - 49% of the particles (by weight) were smaller.

Chapter ten: Integrated approach to the anaerobic digestion process

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Biomass is understood to mean all land and water plants, their wastes or by-products, farmyard wastes (including manures) and the wastes and by-products resulting from the transformation of these plants or of what they produce. This transformation is usually accomplished by the technological processes of the agro- food industries. The production of biomass is primarily derived from the process of photosynthesis - the capture and conversion of sunlight by plants. The energy produced in this fashion is about 10 times the present world energy needs, and about 20 times the food needs, as expressed in terms of energy (Pellizzi 1981). This is so, although the yield harnessed is very low - about 0.1% of the global sunlight radiation reaching earth. Energy transformation processes of biomass can reach much higher degrees (5 - 10%) in some known processes, but not in Nature.

The utilization of biomass for energy conversion poses some difficulties. The actual availability and geographic distribution, the harvesting, transportation, pretreatment and storage problems bring the operation cost to a higher level than most rural people can afford. It is based essentially on the harvesting of the biomass needed for food use only, neglecting the potential utilization of the by-products of these processes. It is time to realize the potential of the agricultural and agro- industrial byproduct, and use them in an integrated resource recovery system. A more integrated approach has to dominate the outlook of energy and food as one plan. Biomass can be used in many ways to generate energy available for human use. Fig 10.1 presents the overall picture of fixing energy from the sun, by utilizing biomass produced by photosynthesis, including organic wastes, for the production of biogas. It must be understood that although biogas is presented here as the only energy generating system, it is not the only way of extracting the energy back from biomass (burning, pyrolysis are some of many examples). Except from direct burning, biogas is the main means of to generating energy from biomass that can bring to rural areas the opportunity to develop industry, in addition to its use for cooking, lighting and heating.

The most efficient use of biogas systems in Developing Countries is incorporation the harvesting of the sun's energy into food and fuel cycles, in an integrated resource recovery scheme.

In some known cases the "Utilization of Agricultural Wastes", in which the integrative approach was applied and used, to obtain an economic operating system, gave an answer that was specifically tailored

to differently structured farms, using all materials existing on the farms (Maramba 1978; Rousseau et al. 1979; Hu Bing-hong 1982; Marchaim 1983; Gunnerson and Stuckey 1983).

Possible integrated systems

The variety of feeds, biogas techniques, and end uses of biogas and slurry results in a large number of possible integrated systems. The interactions between fuel, food and fertilizers in such a system are complex (Figure 10.1). If fuel supply is the primary desired output from such a system, then the nutrients present in the slurry could either be recycled back to the fields to grow more crops and provide residue for feedstock, or be used to grow feedstock directly (Gunnerson and Stuckey 1983). This is a good example how, although all components of the material is used, the output is not optimal and not the most economic one.

[Fig 10.1: Schematic representation of the integrated approach to the utilization of biomass (From Marchaim et al. 1983).](#)

The end use of the biogan also has implications in terms of fuel efficiency. If it is used solely to satisfy cooking and lighting requirements, it will not result in any feedback into fuel production. However, if the Gas is used in a dual fuel engine, the power generated can be used to irrigate fields, resulting in increased agricultural residues available for food and for digestion. In addition, the waste heat produced by the engine can be used as heat for household purposes, or to heat the digester, which would allow a smaller digester to produce the same amount of gas, reducing capital investment and produce a stable quantity of biogas all the year long. The net result could be an energy loop, leading to increased amounts of energy available from a given amount of land. The relative fractions of gas used for cooking and power generation influence the amplitude of this loop, and optimization techniques would maximize the gains from these "feedback" loops.

However, energy must not be looked on as the main product of biogas processes. Food production is influenced by the presence of nutrients within the slurry. The most common method of using this slurry in integrated systems is to recycle it to the fields as a fertilizer/soil conditioner. The method of handling the slurry can influence its efficacy as a fertilizer, and hence the quantity of biomass, food and residuals produced. Examination of the most profitable process to be used on an integrated farm can not be generalized, but must be tailored to the specific farm. There are, for instant, other methods of utilizing the slurry which can increase the amount of food, including re-feeding to animals and growing algae or fish. Also, the end use of biogas is important in this context since utilization of all the gas for pumping irrigation water and powering tractors, as opposed to cooking and lighting, would increase the quantity of food produced from a given amount of land. Yet this would ignore the problems of deforestation and fossil fuels.

Methodology to assess integrated systems

In evaluating an integrated system, it is important to define the boundaries of the system being studied. In many rural situations in Developing Countries, ecosystems can be defined which are relatively closed; i.e. there are little input or output of fuel and feed outside the system. However, in many rural-urban areas the systems are quite "open," with fuel and food input balanced by monetary output. The primary focus of development in recent years in most Developing Countries has been on satisfying the basic needs of the rural poor. The methodology is slightly simpler for closed than for open systems, but this discussion will deal with both systems, with an emphasis on developing new concepts and new ideas for rural areas, in order to develop these sector in particular.

In a typical small village in a rural area, the system boundaries can be said to include the village and all the agricultural land which supports it. All ecological and economic aspects must be considered. Fuel or food entering the system is an input, in addition to solar radiation (which is rarely used by people in villages in Developing Countries), while those leaving the system are the output. In assessing the potential of the integrated system to improve the quality of life within such an ecosystem, the economic evaluation of the food and energy sources, their flows and transformations and the ecological aspects must be considered in a comprehensive manner. The modelling of ecosystems, based on material and on energy flows, and energy conversion efficiencies was pioneered by Odum (1971). Reddy and Subramanian's (1979) rural development approach included:

(a) elucidation of current rural energy consumption patterns;
(b) translation of these patterns into a set of energy needs arranged according to priority;
(c) consideration of feasible technological options for satisfying these energy needs with the available resources;
(d) selection of the "best" option for satisfying each category of need;
(e) integration of the selected options into a system.

Gunnerson and Stuckey (1983) described the model in figures based on data gathered by Ravindranath et al. (1980) on rural energy consumption patterns. This evaluation leads the authors to the selection of a limited set of energy paths, subjected to the following constraints: time dependence of the energy utilizing task; self-reliance; environmental soundness; power requirements of certain tasks; and the availability of the technology. Reddy and Subramanian (1979) evolved an energy scheme, based on this concept, for a community scale biogas unit. In the systems described above, there is a limited role for the optimization of all the techniques involved. In most cases the households have their own system next to the pigsty (and in better cases next to the latrine, too), and use the energy for cooking and lighting their houses, and the slurry as a fertilizer for the fields.

The comprehensive approach involves emphasizing other considerations, in addition to energy, such as nutrient recycling, public health or the environment, and especially the output of the development on the advancement of the rural community by industrializing the village, bringing light and power. The

integrated approach can lead to a system that includes a community system, that gathers all wastes from the village; and by maintaining a central system by experienced technicians and using more sophisticated equipment in order to produce electricity, small agro-industrial plants can be developed in the farm which will attract the new generation. The production of light and power can accelerate the greenhouse and mushroom industries on the village level, and hence use the digested slurry in a much more economic manner, as a substitute for peat- moss. Marchaim, during his visit to China (1990), discussed the question of integrating the separated biogas systems in a certain village in order to generate electricity and power. Some Provincial Rural Energy Officers did not accept the idea, since they estimated that the farmers would not agree to operate in an integrated manner. Other farmers and other officials found the idea very attractive. The success of such a system must be evaluated on a demonstration system in a village.

Existing integrated systems

In recent years, a number of integrated systems have been established in developing countries (Chan 1973; Alviar et al. 1980; Solly 1980; Marchaim et al. 1981; Meta Systems 1981). Probably the best known of these are Maya Farms in the Philippines and Xinbu Village in China.

Maya Farms, which covered 36 hectares and contained 25,000 pigs, 70 cattle and 10,000 ducks, designed and implemented three integrated farming systems, varying in size from a small family farm model to a large commercial feedlot venture (Judan 1981). The family farm is based on 1.2 ha of land with 1.0 ha used for crops (rice or corn) and the rest devoted to a cattle shed, fishpond, biogas works, accommodation and a pigsty containing four sows. The biogas, produced from the swine waste and manure from two water buffalo, is more than enough to supply the family's energy requirements for cooking, and also powers a refrigerator and gas mantle lamp. Solids in the slurry are reefed to the pigs, constituting 10% of their feed, while the liquid slurry is used to raise fish in a 200 m^3 pond, and to fertilize all the cropland throughout the year. This is a very comprehensive and complicated farm to handle for a family.

The medium scale system is based on 12 ha of land and a 48 sow piggery. The gas is sufficient to pump water for the farmhouse and livestock and to irrigate the 12 ha of cropland. The large system was designed for 500 sow units and no agricultural land, approximating an intensive animal feedlot. The gas produced is used for pumping water, lighting the pigpens and operating a feed mill; however, in this case there is a gas surplus amounting to roughly 40% of the output. Various uses for this gas have been suggested. Payback periods varied from 18 to 39 months (for the family farm system).

More efficient systems are possible if all the energy and food within the system, as well as the digested slurry, are fully integrated. With more "open" systems, such as intensive animal feedlots, the prime parameter to consider may be financial returns. This was found as the main constraint in Developing Countries.

Hu Bing-hong (1982) described the Xinbu Brigade in China, which started to install biogas units in 1976, and where 80% of the families use biogas. These units supply some 50% of the families' fuel requirements and, in addition, 17 families use solar roof panels which, with biogas, supply 70 - 80% of their energy needs. The biogas is used for cooking and generating electricity for lighting, and the waste heat from the engine is used to dry silkworm cocoons. Solar dryers are also used to carry out the latter task. The slurry is used to feed fish ponds and fertilize the fields growing mulberry, sugar cane and Napier grass. In addition, some of the slurry is used to grow mushrooms. In the six years the scheme has been in operation, the output from the Brigade (in Yuan) has risen by 150% (Hu Bing-hong, 1982), and the general sanitary conditions of the village have improved considerably.

The integrative approach to the subject of biomass production and utilization raises the demand to reconsider the introduction of biomass from sources which were neglected and abandoned (plant residues) in the past, and even cultivation of some energy crops, to increase the amount of substrate for the process, thus improving the feasibility of an integrated system. Anaerobic biodegradability factors should be considered as well as the quality of the digested slurry produced for further utilizations on a specific locality. The potential benefit of using biomass from different sources i" the possibility of controlling the chemical composition of the digester feed especially the C\N ratio. The fibrous materials (lignocellulosic complex, hemicellulose etc.), although having low biogas production under anaerobic condition, are important in the digested slurry, especially when the material is used as a soil conditioner.

The integrated approach has to evaluate energy as a means to produce more food for the world and to consider food as metabolic energy. It is not surprising that in Nature these two aspects are connected, and this lead. the way to a similar consideration by rural planners. The combination of producing food and energy simultaneously, using the by-products of one as substrate, or complementary to the other, is the right path to be take.

Chapter eleven: The economics of anaerobic digestion

Introduction

For economic analysis, biogas facilities can be broadly divided into two categories: (1) those in which there is a significant economic cost associated with the handling and disposal of organic feedstocks from ecological and environmental aspects, and (2) those in which this cost is negligible. Examples of the first area include sewage disposal, agro-industrial waste treatment, and manure disposal from intensive livestock farming. The second category includes household and community scale plants in rural communities.

With the implementation of more legislation in Developed Countries concerned with environmental and ecological aspects of handling wastes, most industrialized countries already have experience in handling and disposing wastes, but as yet there are only very few cases where data on which to base relevant economic analyses exist. However, the few studies do provide some preliminary indication of economic justification.

Data on different economic aspects of biogas plants in rural areas are accumulating for fertilizer and for fuel uses which were both commonly obtained from the same source material, but are now handled differently. Most of the economic data and analyses come from the Chinese and Indian biogas programs, but other countries are catching up.

One of the forces behind renewable energy technology R & D, including biogas, has been the need to eliminate deforestation by using substitutes for traditional firewood. This secondary benefit creates two problems for analysis: the first is the one of its measurement and evaluation, and the second is one of comparing biogas with other energy technologies that have a different, and commonly smaller array of secondary benefits.

In China, improved sanitation has been a major objective of some biogas programs. Thus, secondary benefits include improved health.

Several reviews of cost benefit studies of biogas have been published, notably Barnett (1978), Sanghi (1979), Mukherjee and Arya (1980), ESCAP (1981), de Lucia and Bhatia (1980), Mazumdar (1982), Gunnerson and Stuckey (1983), Wellinger et al. (1988), Zhijine (1988), de Poli et al. (1988). The early reviews relate mostly to Indian experience while the Chinese economic evaluation study is of Ximbu village in Guangdong province. The latter is for an anaerobic digestion system in general. The Chinese (fixed dome) design has also been evaluated in Thailand (Thongkaimook, 1982) and India (Singh and Singh, 1978). Limited information is available on small scale and community units for the Philippines (Galano et al.; Alicbusan et al.), Nepal (Berger, 1976; Pang, 1978; Pradhan,), Thailand (Prasith-raithaint et al. 1979; Thongkaimook, 1982), Bangladesh (Rahman, 1976), Ethiopia (Tarrant, 1977), Kenya (Pyle, n.d.), Honduras (Roesor, 1979), Pakistan (Qurishi, 1978) and Fiji (Chan, 1975).

Analysis of economic feasibility for biogas construction

The anaerobic fermentation process is an important measure for the solution of fuel shortage in rural area, as well as an important measure for using biomass resources efficiently; for accelerating a common development of agriculture, forestry, husbandry, aquaculture and secondary production; for improving agricultural profitability; for protecting the environment and for good rotation in agricultural production. It is also an important measure for improving and the quality of life, and for the achievement of modernization In rural areas.

One important point for the popularization of a technology is to examine its economic benefits. If profitability is higher, a condition for rapid popularization is available. If economic benefit is low, it is difficult to popularize the technology. The factor of environmental protection is not popularly acceptable, but can be popularized by preferential economic policies, such as in credit and tax.

The production of biogas from biomass by fermentation techniques requires the construction of a biogas pit and a complete system for gas storage, distribution and utilization. Raw materials, labour, etc. for constructing the equipment make up the capital investment of biogas production and utilization. For combined biogas pits, costs for the building of toilets and pigsties need not be included, but the costs of renovating existing toilets for excrement collection should be included.

Economic evaluation of small scale biogas plants requires measuring and valuing the fertilizer and fuel output, then comparing the gross value of output with the costs of plant construction and operation to arrive at a benefit-cost ratio or other index of value.

It is also necessary to include in periodic costs for the maintenance of biogas equipment. The cost of labour and material for managing and maintaining the biogas pits are also included here.

Production and utilization of biogas are beneficial in many ways. They have both direct and indirect economic benefits and social benefits. The direct economic benefit of biogas as a fuel, in place of firewood and coal, is a reduction in fuel expenses. Compared with kerosene lamps, biogas lamps not only reduce the cost of fuel, but also increase light level and improve living quality. Compared with direct burning of stalks, biogas produced from biomass fermentation increases the quantity of organic manure which can be sold to production teams, increasing the direct benefit to farmers.

Biogas production also has many indirect benefits, which sometimes play a very important role in biogas development. For instance, crop stalks, when no longer burned, may be used as animal fodder, increasing the income from animal husbandry, while still providing raw material for biogas production. Farmers can use the time saved from firewood collection for additional production, and thereby increase their income; fermentation effluent can be used as fodder to raise fish, mushrooms and earthworms, and as protein fodder for poultry. Compared with kerosene lamps, biogas lamps improve lighting conditions, making it possible for farmers to embroider, weave and tailor after dark. An investigation of Haian County, in Jiangsu Province, shows that it is the latter benefit that has made farmers actively demand the development of biogas.

Furthermore, biogas development brings about social benefits in many respects. For example, the quantity of animal protein supplied to the society may increase as a result of a reduction of direct burning of stalks and development of animal husbandry. As the problem of fuel for the farmer's daily use is solved, trees are protected and forests are developed. The protection of trees and increase in vegetation areas can reduce soil erosion and improve ecologic balance. The increase in organic manure can result in using less chemical fertilizer, improving soil and increasing production. Environmental improvement in rural area reduces illness and build up people's health. Besides, in regions where biogas is used to generate electricity, cultural, recreation and spare time study conditions can also be improved. Although these benefits are very important for the whole society, they are often not of direct economic benefit to investors in biogas installation, and it is impossible to calculate them accurately in monetary terms. We will not, therefore, consider these benefits in the following economic feasibility analysis.

Economic analysis of simple biogas pit for household use in rural area

(Based on Zhijine (1988) from Energy Research Institute in China)

Most biogas pits used for families in rural areas are 6 - 8 m^3, mainly ambient temperature fermentation models. In the past, most of the biogas pits constructed were simple pits made of clay, lime and sand. These pits have the advantage of readily available materials, relatively simple construction methods and low cost, only 30 - 40 Yuans per pit. However, they are of low quality and they are likely to leak water or gas. In addition, they have a short service time: for those that have good maintenance conditions, the service time is above 10 years, but usually they can only be used for about five years. For those are handled improperly, the service time is even shorter.

Observing the calculation in Tables 11.1 and 11.2 one can notice that the economic benefits of these pits are quite high. In the calculation, 40 Yuans represents the construction cost, at an annual rate of interest 6%, and 5 Yuans the annual maintenance costs, including materials and labour. Table 1. is service time. If all cost" of a biogas based on a 5-year pit are to be paid back in its service time, the average benefit each year must be not less than the R value calculated from the following equation:

$$R = P * \{[i(1+i)^n]\backslash[i(1+i)^n-1]\} + I = 40 * \{[0.06(1+0.06)^5]\backslash[(1+0.06)^5-1]\} + 5 = 1454 \text{ (Yuan)}$$

When the price for straw is 6 cents/kg, this value equals the cost of 242 kg of straw, or the amount of straw consumed by a rural household in one month. Therefore, if a biogas pit operates normally for 1\ months, the direct economic benefit obtained from saving stalks and kerosene for lighting, and from increasing organic fertilizer, can pay back all costs, including interest, within 5 years. When a pit operates normally for more than 6 months per year, total investment can be returned in the same year.

However, economic benefits, great or little, relate to the option selected. When the use of biogas conserves coal, rather than straw, and 25 Yuans per ton of coal is used in calculation, 14.54 Yuans of income equals the price of 580 kg coal, or the amount consumed by a rural household in 4 months. Thus, the pit has to operate normally for 3 months to pay back all costs in 5 years.

In Table 11.2, the service time of a biogas pit is put at 3 years, during which all costs are to be paid back. The average benefit each year is required to be not less than:

$$R = 40 * \{[0.06(1+0.06)^3\backslash]\backslash[(1+0.06)^3-1]\} + 5 = 20.04 \text{ Y}$$

Given the price of straw at 6 cents per kg, the income equals the price of 350 kg straw. This means that, so long as a biogas pit operates normally for 2 months/year, the benefit obtained will pay back all costs within 3 years.

Table 11.1: Costs and benefits (in Yuan) of a simple biogas pit plant (Cost pay back in n=5 years)

YearMaintenance cost (I)	Benefit per year (R)	Coat transferred to next year			
1	40	2.4	5	14.5	32.
2	32.9	1.97	5	14.5	25.37
3	25.37	1.52	5	14.5	17.39
4	17.39	1.04	5	14.5	8.93
5	8.93	0.54	5	14.5	- 0.03

Table 11.2: Cost and benefit (in Yuan) of a simple biogas pit plant (Costs paid back in 3 years)

Year	Coat per year (P)	Interest per year (i=6%)	Maintenance cost (I)	Benefit per year (R)	Coat transferred to next year
1	40	2.4	5	20.00	27.40
2	27.40	1.64	5	20.00	14.04
3	14.04	0.84	5	20.00	-0.12

Economic analyses of cement biogas pits for household use in chinese rural area.

Simple biogas pits can save investment, but they are of low quality and often leak water or gas. Besides, they have a short service time. Because of this, in recent years, a new design of pit is gradually being popularized in rural areas. Constructed of cement and covered with a coating to prevent gas leakage, these pits are of high quality. However, their construction costs are high. The capital cost of a pit is 150-200 Yuans, and the service time is usually above 15 years. At the higher rate of construction cost, at 6% interest, plus 5 Yuans for annual maintenance, an annual average benefit of:

$$R = 200 * \{[0.06(1+0.06)^{15}]\backslash[(1+0.06)^{15}-1]\} + 5 = 25.57 \text{ (Yuan)}$$

will pay back all investment and interest in 15 years. In regions where price of straw is 6 cents/kg, the benefit equals the cost of 427 kg straw. Hence, as long as the biogas pit operates normally not more than 3 months a year, the benefit obtained from saving stalks and kerosene and from increasing fertilizer will pay back all costs in 15 years. Since, on average, these pits can operate normally 8 months in the year, when used for cooking, 1300 kg of stalks are saved, that is, 78 Yuans at 6 cents/kg; when for lighting, it can save 4 Yuans of kerosene: the average direct economic benefit available is 82 Yuans annually. As analyzed in Table 11.3 the investment cost (including interest) of a biogas pit plant can all be paid back in less than 3 years.

If biogas replaces coal, the annual average benefit of 25.6 Yuans equals the cost of one ton of coal. Only when the pit operates normally for more than 6 months can all costs be paid back in 15 years by its direct economic benefit.

Economic analysis of community biogas plants in China.

As a result of the appearance of all kinds of specialized households, biogas pit plants for household use no longer meet the demands of economic development in rural areas. Quite a number of rural households no longer rent farm lands, or raise livestock, so they have no raw material to produce gas. There are, however, other specialized households that raise livestock (pigs, cows and chickens, etc.) and consequently have a great amount of animal excrement as raw materials for gas production. Centralized biogas supply is therefore a developing trend for energy production in China's rural areas.

Table 11.3: Cost and benefit (in Yuan) of cement pit plant (when operated normally for 8 months per year)

Year	Coat per year (P)	Interest per year (i=6%)	Maintenance coat (I)	Benefit per year (R)	Coat transferred to next year
1	200	12	5	82.00	135.00
2	135	8.1	5	82.00	66.10
3	66.1	3.97	5	82.00	-6.93

Although the centralized biogas supply system has many advantages, its capital cost is much greater than that of the family biogas pits. According to the systems constructed, the average investment for a household is 300 - 600 Yuans, up to double that of the family biogas pit plant. As a result, its economic benefit is much lower. At present, centralized biogas supply systems are developed as a public welfare service, irrespective of their economic benefits. However, there must be some economic benefits, if the system is to be expanded rapidly. Up to the present day, the largest centralized biogas supply station is in Qianjin Farm, in Chong-ming County. At this station, 65 50 m biogas pits have been built, supplying gas to 720 households of farmers for daily use.

Investment in this system was 547,000 Yuans, and the annual rate of interest is 6%. Operating costs include wages for six workers and maintenance costs: 6600 Yuan per year. The direct economic benefit is that the cost of coal it replaces equals about 40,000 Yuans per year. Livestock and poultry excrement is used as raw material for fermentation, which ha" the same benefit as a fertilizer before and after fermentation. Because of this, its input of cost equals the output of benefit and therefore is not considered in the analysis. Table 4 shows that when calculations are based on the index above, the payback period for capital will be 90 years, if only the economic benefit of replacing coal is taken into account.

Table 11.4: Analysis of economic benefit of community biogas plant at 10,000 Yuan (compared with coal saving option)

Year	Cost per year (P)	Interest per year (i=6%)	Maintenance coat (I)	Benefit per year (R)	Coat tranaf erred to next year
1	54.70	3.28	0.06	4.00	54.64
2	54.64	3.28	0.06	4.00	54.58

If the system provides biogas to rural residents, assuming that each household saves 2000 kg straw (supplying gas all the year round) the annual economic benefit of a household would be 120 Yuans at 6 cents per kg straw, and the total benefit to 720 households would be 86,400 Yuans. On this basis, all cost could be paid back in less than 10 years (Table 11.5). According to economic analysis, the development of community biogas plants in rural areas is economically feasible. However, when compared with the use of coal, its economic benefit is not great. It is therefore necessary to make further efforts to reduce the investment and construction cost of centralized biogas supply systems, and increase gas production. Without higher economic benefits it can be only run as a welfare service.

Table 11.5: Analysis of economic benefit of community biogas plant at 10,000 Yuans (consistent with straw-saving option)

Year	Cost per year (P)	Interest per year (i=6%)	Maintenance cost (I)	Benefit per year (R)	Coat transfyear erred to next year
1	54.70	3.28	0.06	8.64	50.00
2	50.00	3.00	0.06	8.64	45.02
3	45.02	2.70	0.06	8.64	39.74
4	39.74	2.38	0.06	8.64	34.14
5	34.14	2.05	0.06	8.64	28.21
6	28.21	1.69	0.06	8.64	21.92
7	21.94	1.32	0.06	8.64	15.26
8	15.26	0.92	0.06	8.64	8.20
9	8.20	0.49	0.06	8.64	0.71
10	0.71	0.04	0.06	8.64	-7.23

Community level plants in India

The introduction of large scale (greater than 40 ma) plants for use by rural communities has been prompted by two important considerations. First, the alternative of a household plant is not an option for most Indian households. Only 5% of the cattle-owning households have the minimum 5 animals needed to provide feedstock (Prasad et al., 1974), and perhaps even fewer could bear the additional cash outlay involved in the substitution of biogas for firewood and dung, previously collected by family labour. Second, economy of scale is one of a number of potential techno-economic advantages of community over household plants, though this partly offset by the larger volumes of dung required at one site, and in the greater organizational requirements.

Two community plants have been evaluated in some detail; one at Fateh Singh Ka Purwa in Uttar Pradesh by Bahadur and Agarwal (n.d.), Ghate (1979), and Bhatia and Niamir (1979), and one in Xubadthal, Gujarat by Maulik (1982). Evaluating community plants has the same drawback as in household units, of valuing input and output, so it is not surprising that three evaluations of the Uttar Pradesh plant arrived at three different economic benefit-cost ratios; 1.14:1, 1.54:1 and 0.6:1. Moulik's (op. cit.) financial analysis of the Gujarat plant did not include a final estimate of financial viability, but it was evident from current performance that the profit from plant operation would not meet the loan and

interest payments due. Other analyses agreed that the plant was not financially viable, though Ghate (op. cit.) suggested that at least part of the deficit on the costs of cooking, lighting and water supply (from a biogas powered tube well) could be met through a surplus generated by the dual fuel engine used for crop processing.

Financially nonviable plants can be justifiably supported through state subsidies, if overall analysis is sufficiently positive. The basis for an accurate economic benefit-cost analysis is still lacking, however.

One important difference from the analysis of household plants is the greater variety of possibilities for the use of gas from a community plant. Gas availability varied in the Fateh Sing] Ka Purwa plant from below 1900 ft^3/day in winter, to above 2700 ft in summer (Bhatia and Niamir, op. cit.). This gas was used for cooking, a generator to supply lighting and to power a tube well, and a dual fuel engine running a flour mill, a thresher and a chaff cutter. The proportion of gas distributed to these different end uses has been considered to be a critical determinant of both the financial and social worth of the plant because both market and shadow prices of the gas will vary. An alternative approach to economic evaluation assumes the highest value use until the demand is met, then the next, etc. This higher use(s) requires a unique fuel characteristic with unique replacement value. The combination of end uses that will maximize benefits depends upon the assumptions used to value gas put to different end uses. In their social analysis, all three studies used the shadow price of soft coke or coal to value biogas in cooking. They arrived at three different estimates: 11.6, 15 and 38.3% as the share of cooking in the total benefits. Bhatia and Niamir (op. cit.) also used the price of dung and firewood to value biogas in cooking, giving a second estimate of 63% of total benefits from this end use. In this second estimate, dung was valued using the shadow price of imported fertilizer. Under this assumption over half of the total benefits were due to the use of dung for fertilizer, instead of for cooking which is now carried out using biogas. Since cooking uses about 60% of the gas, these widely differing percentages (11.6 to 63%) can be used to support a case for or against the use of biogas for cooking in preference to other end uses. Different initial investment and operating costs will also affect the calculation). Financial analysis of the value of different end uses was less equivocal; non-cooking uses, particularly substitution for diesel fuel, are better.

What these ambiguous results demonstrate is the inability of social and financial analysis to determine policy in the absence of a strategic energy policy framework. The possible deforestation and loss of agricultural output associated with the use of firewood and dung has to be evaluated in conjunction with the foreign exchange costs of diesel imports in the case above, but this is only one example of the types of valuation implicit in all energy policy decisions. A second, and equally crucial limitation, is the difficulty analysts face in incorporating secondary benefits. Some, such as health benefits, are extremely difficult to quantify, while others, such as improved community spirit through a successful biogas program, are impossible. In the community programs discussed above, a variety of secondary benefits were acknowledged by participants as being very important to their perception of the value of biogas plants. This was particularly true of women who benefitted from improved kitchen conditions, and savings on cooking time.

The technology evaluated in the above studies was an expensive KVIC design. In a Southern Indian village a community plant is being built to meet the specific village energy requirements, and financial viability is possible (Lichtman, 1983). It is worth noting, however, that both the plants discussed above were also financially viable on paper. A second, and critical feature of the Southern Indian program is the involvement of the villagers in the planning of the biogas plant. In both the plants discussed above the chief reasons for their difficulties were organizational, rather than economic or technical. Moulik in the Gujarat study, and Bahadur and Agarwal, in the Uttar Pradesh study, provide detailed descriptions of numerous organizational and operational problems that were related to village social structure, and the relationship between the villagers and the implementing agency. All the authors of these studies agree that the solution of such social problems with community plants requires the involvement of users from the very first stages of planning.

Experience of economic evaluation in other countries

Evidence on household and community plants from other countries is extremely scarce and provides little additional knowledge that might resolve some of the uncertainties that the Indian studies have raised. Only a few of the studies available were based on actual user experience. Rahman (1976) gives a breakdown of costs and benefits of a modified Indian design used in Bangladesh, without any firm conclusion on its economic viability. However, with a net annual operating profit of Tk.581, and an initial construction cost of Tk.7,600, only very low interest rates on a loan for construction would make the plant financially viable.

Of three Nepalese desk studies based on Indian design (three cubic meter) plants, only Berger (1976) estimated a positive benefit-cost ratio (1.67:1), while Pradhan (n.d.) and Pang (1978) argued that construction cost reductions were

critical if biogas was to be financially feasible for any but the richer farmers.

In Thailand, an empirical study of Indian design plants by Prasith-raithsint et al. (1979) found that household plants on average had a payback period of 5 years. No other estimates of economic worth were calculated. No benefits were claimed for the slurry, as this we" not used by plant owners. The high cost of plant-, a lack of technical know-how, the availability of other fuels, and the shortage of dung were the main reasons given by the 94.5% of current nonusers who said they did not want a plant.

A desk study by Roeser (1979) of two household plants in Honduras showed that the economic viability of the pants depended critically upon the relative time spent on dung and firewood collection. At low dung collection times, the larger plant (360 ft^3) was viable. The smaller plant (180 ft^3) was viable only when cooking, rather than lighting, was the use adopted. However, in the absence of subsidized kerosene for lighting, use of biogas for lighting was viable at low dung collection and preparation times. He recommended further study before diffusing biogas, and drew attention to the importance of comparing the use of a biogas plant for cooking with the use of an improved stove. If the fuel efficient "Lorena" stove could reduce firewood collection time to one hour per day, the use of biogas for cooking was not as profitable to the household as use of the stove.

Tarrant (1977) undertook a comprehensive evaluation of the use of a community plant for generation of electricity in Debarek, Ethiopia. He concluded, using three different measures of social worth, that the project was viable at current oil prices (the fuel used to value biogas), but that the project was not financially viable. However, the detailed figures provided on financial and social costs and benefits suggest that a subsidy to cover the financial deficit would still leave the project socially viable. He concluded that more detailed field evidence was required on three critical parameters; electricity demand projections, slurry transport costs, and the value of dung, to firm up the estimates presented.

Economic analysis on electricity generation with biogas in Chinese rural areas

China has a vast rural territory and the coverage of large electricity grids is limited. At present, there are approximately 50% households in rural area which do not have electricity. Even in regions connected with the grid, electricity supply is not always guaranteed, because of electricity shortage and restrictions on consumption. Thus, in areas where biogas resource is rich, the development of small size biogas electric power station to provide electricity to rural areas is of great interest to improve the quality of life, and to increase cereal and fodder production, as well as to facilitate the establishment of country town industries that consume less electricity.

When the price of electricity from the large grids is compared with that of a biogas electric power station, the cost of diesel oil for biogas-diesel dual burning generators is 4 cents per kw/h, while electricity provided by the grid for agricultural production costs only 5 cents. Hence, biogas generation of electricity provides almost no benefit. Though the price difference of electricity for residential use is great, electricity is supplied only 3 - 4 hours a day and economic benefits are low. As a result, the investment in biogas would never be paid back, in the present situation.

When compared with diesel oil generation, biogas electric generation may have a rather high economic benefit. But the common problem in biogas electric generation in rural area is that the capacity of generation unit and biogas pit plant do not form a complete system. A generation unit with a capacity of 1 kw is provided with a 20-25 m biogas pit plant, with ambient temperature fermentation. One kw generation capacity can only provide 3-5 kwh of electricity each day. For 360 days of a year, it can only generate 1000-1500 kwh of electricity. Since its equipment utilization hour is too low, its economic benefits are reduced.

Results of similar calculations show that biogas generation equipment has a life of not more than 2000 hours. This means its direct economic benefit can not pay back the increased investment cost based on the above assumptions. If indirect benefits, such as if electric generation would stimulate industry and sideline industry development, and increase farmer's incomes as plus social benefits, were taken into account, and where diesel oil supply is limited, the construction of biogas electric power station would be beneficial. From the economic analyses, we see that higher yield gas producing fermentation processes must be developed, and utilization hours of generation equipment should be increased for biogas electric generation to be economically attractive.

Industrial and commercial feedlots

Developed countries using anaerobic digestion to treat industrial wastes include Israel, the United States, the Federal Republic of Germany and the Netherlands. In developing countries only a few large scale units are known to exist, although some laboratory work has been carried out in India, Brazil and China. The largest number are in China, and Marchaim (1990) obtained some tentative economic data during a recent study tour in China and Thailand.

Experience in the use of anaerobic digestion to treat the manure generated in commercial feedlots in Developing Countries is also limited, although the one case of Maya Farms in the Philippines has been reasonably well documented.

Maya Farms is one of the pioneers of large scale biogas applications in the developing countries, and the technology forms an integral part of an intensive animal rearing farm located within Metropolitan Manila. Manure from 22,000 pigs is fed into a variety of batch and continuously fed digesters which produce a total of 66,000 cubic feet of biogas per day. The gas produced is used directly as a fuel in the processing plants, or substitutes for gasoline in a number of engines which drive a variety of equipment and machinery. In addition, some of the gas is used in motors to generate electricity which is used on site.

The "slurry is separated into two fractions, liquid and solid, and the liquid is used to fertilize crops and feed fish ponds, while the solids are reefed to pigs, cattle and ducks. These solids supply around 10 to 15% of the total feed requirements of the pigs and cattle, and 50% of the feed for the ducks.

Based on actual operating data from Maya Farms, Judan (1981) estimated the benefits from small (4 sows), medium (48 sows), and large (500 sows) farms using biogas unit" in the Philippines. In hi" analysis he calculated benefits in terms of savings on inputs of fuel, feed and fertilizer that would have been necessary in the absence of the biogas unit. For the small farm, 27% of the benefits came from fuel savings, 54% from animal feed savings, and 19% from the fertilizer saved. In the medium farm, the respective savings were 36, 52 and 12%, while in the large one they were 21, 79 and 0%, since in this case no crops were fertilized. The most important benefit is derived from re- feeding the slurry solids to the pigs.

These results are qualitatively consistent with Israeli experience in which feeding a 12% solids slurry from thermophilic digestion of dairy manures to fish ponds or beef feedlots provided most of the benefits (Marchaim, 1983).

Judan (op. cit.) provides a summary statement of the investment and operating expenses of Maya Farms, and estimated payback periods of 39 months (small), 21 months (medium), and 30 months (large). This study provides a strong economic case for the development of integrated systems that efficiently utilize all the outputs from a biogas unit by substituting for purchased farm inputs. However, since this conclusion rests on the benefits accruing from re-feeding the sludge solids to animals, caution should be exercised as there is still some controversy about the effects of re-feeding (Ward 1982).

One study evaluated experience with anaerobic digestion in industrialized countries with particular reference to its transferability to Developing Countries. Marchaim et al. (1981) describe a conceptual 200 m thermophilic digester system in Israel being fed cattle manure (15 to 18% total solids), where the biogas was used for heating and power generation, and the slurry to fertilize crops, feed fish, cultivate mushrooms, and as a partial feed for sheep and calves. Their positive economic analysis also depended on the income generated from the slurry in the form of feed. When no income was available from the slurry, the "break even" point (i.e., when the net present value of the whole operation is zero) occurred when the price of gasoline was US$1.22 per gallon. If all the slurry were sold as feed, then the plant would be economically viable at any gasoline price above US$0.23 per gallon. They claimed this analysis would be valid in similar situations in Developing Countries, e.g., a village cooperative in Gujarat, India; however, this claim should be regarded with some caution since the technology used (thermophilic, continuous mixing, high loading rates) is quite sophisticated, and may cause problems in Developing Countries.

Fig. 11.1: Schematic system for an anaerobic methanogenic thermophilic fermentation process for farm wastes. A. Macerating system for rumen content and manure. B. Waste pit. C. Pump. D. Heat exchange system. E. Digestion system. F. Biogas mixing system. G. Intermediate container. H. Slurry separator. J. Compressor. K. Biogas storage system. L. Steam/electricity generator. M. Solid (Peatrum) fraction collector. N. Liquid fraction collector.

Feasibility estimate for a turn-key community plant

An economic feasibility study must be based on the know-how acquired on laboratory scale and pilot-plant scale, and is performed after several years of experience in full scale and commercial plants of the anaerobic methanogenic fermentation of diverse agricultural wastes (dairy manure, poultry manure, cotton stalks, slaughterhouse wastes, etc.). The anaerobic digestion system was developed in order to solve the acute question of wastes in feedlots of farms - how to get rid of an ecological problem that caused in many cases high expenses in fines and levies to the local health authorities. A waste utilization system is made up of three main sections: the microbiological, engineering and economic sections. The overall goal of the integrated system is to develop a method that will utilize the manure of cattle and other agricultural wastes, converting them into biogas and other materials that have marketable value, while solving the ecological problem of the farm wastes. For this purpose, an example of the anaerobic thermophilic methanogenic fermentation is described here. The Figure below represents an integrated anaerobic thermophilic digestion process schematically, based on Klinger and Marchaim (1987).

Continue

Economic evaluation study for a full-scale village-community plant

The products of the plant
Feasibility estimate for a turn-key farm waste utilization system

The main components of a turn-key system include:

Infrastructure

The village or farm must make available a reasonably flat area of 200m^2 with 30 cm depth of gravel over the area. An electrical supply of 100-200 amps and a water-pipe of 2-3 inches is needed next to the plant.

Construction

Foundations and columns according to soil structure, with 50-100 m^2 of concrete floor. A second small concrete floor (50-100 m) for the Peatrum, with a wall around, for the separation system. A larger concreted area will be needed, in addition, if the Peatrum is to be composted (for greenhouses) on site.

Charging system

Chopping machine, pump, mixer, stone-trap, piping and accessories.

Heating system

Boiler, heat-exchangers, circulation pump, regulation and control system, insulation and accessories. There is the possibility of using hot water from an electricity generator supplied separately.

Digestion system

Appropriate volume of digester(s), biogas circulation system for mixing, insulation with a thickness of 5.0-7.5 cm. polyurethane, outlets for digested slurry and biogas, piping, control and regulation of temperature and pressure, and accessories.

Biogas system

Blower, gas traps, pas meter, piping, compressor (10 atm.) and a gas storage of 15 m^3 (depending on needs), gas regulators, pressostats and accessories under suitable cover.

Slurry separation system

Slurry container, separation system with elevated stage, controls and accessories.

A total energy generator system

There is the possibility of using the biogas to generate electricity and hot water (to be used for the digestion system), based

on current biogas co-generation.

<u>Control and monitoring system</u>

An electricity panel, a control container, electrical accessories in the area, computerized control system, including digital temperature meter and temperature-controlled heating system, controls for mixing system, gas pressure and biogas storage, gas meters, alarm system, etc.

The products of the plant

1. Biogas.

One end-product of anaerobic digestion is a gas that consists of 62-65% methane (CH_4) and under 40% carbon dioxide (CO_2). This gas can be used as an energy source and has, without scrubbing, a caloric value of 5,800 Kcal/m . Scrubbing is only feasible for engine use. It has been used in burners for hot water or steam generation and in systems that produce electricity and hot water or steam (a co-generation system). In some cases, the separation of methane from carbon dioxide is feasible, and then not only the methane is used as an energy source, but also the carbon dioxide, to enrich the atmosphere of greenhouses or for cooling purposes. This separation process is only worthwhile if on- site use for carbon dioxide is essential.

2. Separated Slurry (Peatrum or Cabutz).

The digested slurry is sieved on a vibrating sieve, and the fibrous fraction of the digested cow manure, which consists of 25-40% solids, is collected. A special treatment of washing and adding limestone is used to make a very good substitute for peat moss, used as a casing soil in the champignon mushroom industry. It can also be used as an organic fertilizer and soil conditioner for gardening, though it has a higher value for nurseries and greenhouses, where it is used as a substitute for sphagnum peat moss. In this case, a secondary treatment of composting is essential, which can be done inside or outside the plant. Peatrum or Cabutz are already commercially known product in Israel, and therefore its price is estimated here at 25% lower than the price in Israel for sphagnum peat-moss.

3. Liquid Fraction.

The liquid fraction of the sieved digested slurry can be used as an excellent fertilizer of balanced N.P.K. content. Its value has already been established in experimental stations, but transportation is expensive and therefore no economic value is as yet attributed to this product in the context of the feedlot-farm operation.

4. Slurry

It has been established that the digested slurry, before separation, has a high value in aquiculture as a substitute for pellet feed, replacing up to 50% of the commercial feed. Only in special cases can the slurry be used for this purpose: it must be used in the near vicinity of the plant.

Feasibility estimate for a turn-key farm waste utilization system

The following tables give the basis information on several proposed turn-key plants, based on Israeli estimations. The estimated quantities of wastes which will be processed in the different plants are based on data presented in Table. 11.6.

Table 11.6: Estimated quantities of wastes from 100 cows and 50 calves in a feedlot with shelters and with bedding

	Manure on concrete	Manure +straw	Total quantity per day
Quantity per cow (liters per day)	40.0	6.25	46.25
Quantity per calf (liters per day)	8.0	1.90	9.90
Per cent of dry matter	12.5	16.0	
Quantity of dry matter per cow (Kg)	5.0	1.0	6.0
Quantity of dry matter per calf (Kg)	1.0	0.3	1.3
Total quantity per 100 cows + 50 calves m^3 per day			5.125
Total quantity per 100 cows + 50 calves tone per day			0.665

For each digestion system described below, quantities are derived from the above table by multiplying the figures by the number of head of cattle. Each system is based on charging the digesters 5 days a week with a volume which is one eighth of the digester volume per day. The average retention time will therefore be 11.2 day

Table 11. 7: Several digestion systems for farm wastes

Farm type	No. of heads cows & calves	Quantity of waste generated daily (m^3)	Quantity of dry matter generated daily (tones)
a	100 + 50	5.125	0.665
b	300 + 150	15.375	1.995
c	500 + 250	25.625	3.325
d	1000 + 500	51.250	6.650

Table 11.8: Plant sizes and estimated investment for each of the a-d farms

Slaughterhouse type	Digestion system suggested (m^3)	Estimated investment in ordinary plant (U.S.$)
a	50	150,000
b	150	350,000
c	250	500,000
d	500	800,000

Table 11.9: Expected quantities of produce from a-d farms. Based on the schematic description of a plant for agricultural waste utilization (11.1)

Farm type	Peatrum m^3	Liquid fraction m^3	Biogas m^3	Electricity RWH	Not water 1
a	390	2,210	44,200	54,600	16,692
b	1170	6,630	132,600	163,800	50,076

c	1950	11,050	221,000	273,000	83,460
d	3900	22,100	442,000	546,000	166,920

* Energy is expressed in Diesel fuel equivalents for generating hot water.

Fig. 11.2: Schematic description of a plant for agricultural waste utilization (with 1,000 cows and 500 calves)

Table 11.10: Annual expenses for several anaerobic digestion systems

	PLANT SIZE			
	a	b	c	d
	in U.S. $ x1,000			
Investment	(150)	(350)	1500)	(800)
PMT, 7 year.,12%	33	77	110	175
Salaries	10-15	10-15	20-25	35-40
Water	1-2	1-2	3-5	5-8
Electricity	1-2	2-3	3-5	5-8
Maintenance, 2%	3	7	10	16
Insurance,1%	1	3	5	8
Waste water treatment	-	1-2	3-5	5-8
Acid. for sanitation	-	1-2	2-5	5-8
Total annual current				
Expanses	16-23	25-34	46-60	79-96
Total annual exponses	49-56	102-111	156-170	254-271

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Economic analysis

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A simple economic model was used to examine the feasibility of the "Thermophilic Anaerobic Digestion of Agricultural Wastes" Pants. We examined different sizes of plants suitable for different slaughter houses ranging from slaughter- houses that slaughter 100 to 1,000 heads of cattle per day, 5 days a week. Based on previous experience and know-how, quantities of wastes generated by 100 head were estimated (Table 11.6). Quantities can vary according to cattle weight and local feeding and slaughtering regulations. We examined four sizes of slaughter-houses slaughtering 100, 300, 500 and 1,000 head per day. For each of them the quantities of wastes were estimated (Table 11.7) and the proposed plant was planned, and the estimated investment defined accordingly (Table 11.8). This estimated cost of the plant must be examined on site in the light of local conditions. The quantities of the products of the different pants. (Table 11.9) were calculated on the basis of the schematic mass balance diagram presented. The description of the plant outputs are reviewed in the background material. The uses of the liquid fraction were not taken into account although in many countries it is considered a valuable fertilizer. The annual expenses of the "Thermophilic anaerobic digestion" systems are based on our experience from similar systems in operation (Table 11.10). In the calculations we took into account 12% interest and a 7-year depreciation time. Both are quite high for such a project and take into consideration the risk of a new technology. We included in the expenses some money for additional water treatment and, in the event of a breakout of Salmonella or other pathogenic bacteria infection, an organic acid treatment that we examined as an efficient way of decontamination. The feasibility calculations were done first in a simple way in which the different-sized plants were examined for their annual profit according to several income and expense alternatives (Table 11.11). An example of the Net Present Values and the Internal Rate of Return for some different sized plants are given in Tables 11.12, 11.13, 11.14 and 11.15). The average profit minus the average expense was used for these calculations. The calculations were first performed for a plant that is not obliged to pay fines or levies to the local municipality and then at several levels of levies.

Table 11.11: Feasibility calculations for a communal several sized systems

INVESTMENT. $	150,000	350,000	500,000	800,000
pmt. 7,12%	32,868	76,691	109,559	175,294

YEARLY EXPENSES OF SEVERAL ALTERNATIVES. $				
ALT' A	16,000	25,000	46,000	79,000
ALT' B	20,000	30,000	53,000	87,000
ALT' C	23,000	34,000	60,000	96,000
YEARLY INCOMES OF SEVERAL ALTERNATIVES. $				
ALT' D	30,000	90,000	150,000	300,000
ALT' E	35,000	105,000	175,000	350,000
ALT' F	41,000	123,000	205,000	410,000
YEARLY PROFIT FOR SEVERAL ALTERNATIVES (IN U.S.$)				
PROFIT FOR LOWER INCOME. ALTERNATIVE D, $				
EXPENCES. $				
ALT' A	(18,868)	(11,691)	(5,559)	45,706
ALT' B	(22,868)	(16,691)	(12,559)	37,706
ALT' C	(25,868)	(20,691)	(19,559)	28, 706
PROFIT FOR MEDIUM INCOME ALTER NATIVE E , $				
EXPENCES. $				
ALT' A	(13,868)	3,309	19,441	95,706
ALT' B	(17,868)	(1,691)	12,441	87,706
ALT' C	(20,868)	(5,691)	5,441	78,706
PROFIT FOR HIGHER INCOME ALTERNATIVE F, $				
EXPENCES. $				
ALT' A	(7,868)	21,309	49,441	155,706
ALT' B	(11,868)	16,309	42,441	147,706
ALT' C	(14,868)	12,309	35,441	138,706

Table 11.12: Net present values and internal rates of return for a plant where 100 heads of cattle are slaughtered per day with several benefits from saving levies.

	IN U.S..$

YEAR				
	LEVIES	0	25,000	40,000
INITIAL	INVESTM	(150,000)	(150,000)	(150,000)
1		15,000	40,000	55,000
2		15,000	40,000	55,000
3		15,000	40,000	55,000
4		15,000	40,000	55,000
5		15,000	40,000	55,000
6		15,000	40,000	55,000
7		15,000	40,000	55,000
NET PRESENT VAL				
%.	YEAR			
12	1	(136,957)	(115,217)	(102,171)
12	2	(125,614)	(84,972)	(60,586)
12	3	(115,752)	(58,671)	(24,423)
12	4	(107,175)	(35,801)	7,024
12	5	(99,718)	(15,914)	34,369
12	6	(93,233)	1,379	58,147
12	7	(87,594)	16,417	78,823
I.R.R 7 YEARS		-0.082	0.186	0.312
I.R.R 5 YEARS		-0.194	0.104	0.243

Table 11.13: Net present values and internal rates of return for a plant where 300 heads of cattle are laughtered per day with several benefits from saving levies.

		IN U.S. $				
YEAR						
	LEVIES	0	25,000	40,000	55,000	70,000
INITIAL	INVESTM	(350,000)	(350,000)	(350,000)	(350,000)	(350,000)
1		75,000	100,000	115,000	130,000	126,000
2		75,000	100,000	115,000	130,000	126,000
3		75,000	100,000	115,000	130,000	126,000

4		75,000	100,000	115,000	130,000	126,000
5		75,000	100,000	115,000	130,000	126,000
6		75,000	100,000	115,000	130,000	126,000
7		75,000	100,000	115,000	130,000	126,000
NET PRESENT VAL						
%	YEAR					
12	1	(284,783)	(263,043)	(250,000)	(236,957)	(240,435)
12	2	(228,072)	(187,429)	(163,043)	(138,658)	(145,161)
12	3	(178,758)	(121,677)	(87,429)	(53,181)	(62,314)
12	4	(135,877)	(64,502)	(21,677)	21,147	9,727
12	5	(98,588)	(14,784)	35,498	85,780	72,372
12	6	(66,164)	28,448	85,216	141,983	126,845
12	7	(37,969)	66,042	128,448	190,855	174,213
I.R.R 7 YEARS		0.113	0.211	0.265	0.318	0.304
I.R.R 5 YEARS		0.023	0.132	0.192	0.249	0.234

Table 11.14: Net present values and internal rates of return for a plant where 500 heads of cattle are laughtered per day with several benefits from saving levies.

IN U.S. $						
YEAR						
	LEVIES	0	40,000	55,000	75,000	100,000
INITIAL	INVESTM	(500,000)	(500,000)	(500,000)	(500,000)	(500,000)
1		122,000	162,000	177,000	197,000	197,000
2		122,000	162,000	177,000	197,000	197,000
3		122,000	162,000	177,000	197,000	197,000
4		122,000	162,000	177,000	197,000	197,000
5		122,000	162,000	177,000	197,000	197,000
6		122,000	162,000	177,000	197,000	197,000
7		122,000	162,000	177,000	197,000	197,000
NET PRESENT VAL						
%	YEAR					
12	1	(393,913)	(359,130)	(346,087)	(328,696)	(328,696

12	2	(301,664)	(236,635)	(212,250)	(179,735)	(179,735
12	3	(221,447)	(130,118)	(95,869)	(50,205)	(50,205
12	4	(151,693)	(37,494)	5,331	62,431	62,431
12	5	(91,037)	43,049	93,331	160,375	160,375
12	6	(38,293)	113,086	169,853	245,543	245,543
12	7	7,571	173,983	236,394	319,603	319,603
I.R.R 7 YEARS		0.155	0.260	0.297	0.344	0.344
I.R.R 5 YEARS		0.070	0.186	0.226	0.279	0.279

Table 11.15: Net present values and internal rates of return for a plant where 1000 heads of cattle are slaughtered per day with several benefits from saving levies.

IN U.S. $						
YEAR						
	LEVIES	0	40,000	55,000	75,000	100,000
INITIAL	INVESTM	(800,000)	(800,000)	(800,000)	(800,000)	(800,000)
1		263,000	303,000	318,000	338,000	313,000
2		263,000	303,000	318,000	338,000	313,000
3		263,000	303,000	318,000	338,000	313,000
4		263,000	303,000	318,000	338,000	313,000
5		263,000	303,000	318,000	338, 000	313,000
6		263,000	303,000	318,000	338,000	313,000
7		263,000	303,000	318,000	338,000	313,000
NET PRESENT VAL						
%	YEAR					
12	1	(571,304)	(536,522)	(523,478)	(506,087)	(527,826)
12	2	(372,439)	(307,410)	(283,025)	(250,510)	(291,153)
12	3	(199,512)	(108,183)	(73,934)	(28, 270)	(85,351)
12	4	(49,141)	65, 058	107,883	164,983	93,608
12	5	81,617	215,703	265, 985	333,028	249,225
12	6	195,319	346,698	403,465	479,155	384,543
12	7	294,190	460,607	523,013	606,222	502,211
I.R.R 7 YEARS		0.266	0.326	0.348	0.378	0.341

I.R.R 5 YEARS	0.192	0.259	0.283	0.315	0.275

Summary and conclusions of a full-scale village-community plant

1. Based on the economic feasibility study performed , we can conclude that an anaerobic digestion system in a farm is economic when:

1.1 It can sell the Peatrum (the solid fraction of the digested slurry at a reasonable price to gardening, greenhouse or mushroom producers; or:

1.2 When fines or levies are paid to the local health authorities. The higher this amount, the more the system returns.

2. The liquid fraction of the digested slurry has value as a fertilizer or as a digestion accelerator, but since this is still in the research and development stage, no commercial value has been attributed.

3. The reduction by several orders of magnitude of pathogenic bacteria and the elimination of Salmonella by the thermophilic anaerobic process is a great advantage which has not been calculated in the "saving" of money.

4. The lower the fines and levies at a plant, the lower the initial investment that can be considered.

5. The main income from this plant, apart from the savings in fines and levies, is from the peatrum, which is a substitute for enriched peatmoss in nurseries, or casing soil for the mushroom industry.

6. When a system is considered for a feedlot , an intensive initial survey must be performed to examine all aspects of such an integrated project.

Conclusion from the chinese experience

1. From the economic analysis we notice that simple biogas pit plant involving low investment, quick returns and a short pay back period offers the highest economic benefit, but it requires much maintenance and renewal work, while its management is complex. Consequently, it is unsuitable for consideration in long term development.

2. The household cement biogas pit also offers a high economic benefit. It is now the popular design in rural areas in China. However, it does not meet the need of the new situation in rural areas, as the farmer's income increases and production becomes more specialized.

3. Centralized biogas supply systems are an important method of supplying energy for living in a modernized rural area in the future. At present, however, its economic benefit is low. It is necessary to study new fermentation processes, to increase its economic benefit.

4. The direct economic benefit of biogas electric generation is not high with present techniques. It can be built suitably when its indirect economic benefit, or social benefit is taken into account. It can be popularized only when more efficient gas producing equipment is developed, the utilization rate of generating facilities increased and the economic benefit of biogas generation are improved.

Problems in evaluating the community indian plants

For a plant in India or other Developing country land costs have been specified in some detail by KVIC for the full range of sizes of the only design promoted on a large scale in India. The total (KVIC estimated) construction costs of a plant are very high (Rs 2,332 for 2 m at 1975 market prices), and proponents of biogas plants reduce these costs in economic analyses by presuming that land for the site and labour used in construction have no opportunity cost. Except in the most densely settled villages, land can be treated at no cost since the area involved are so small. However, the assumption of a zero shadow wage of labour will be valid only when labour is completely idle because of the lack of work opportunities, not through choice.

Evidence on adoption behaviour suggests that in practice the financial cost of construction materials in relation to farm cash incomes is the most important factor. To make these costs manageable, KVIC has organized subsidies to farmers. Since no farmer can purchase a plant without a loan, it means in effect that at current construction costs they are only accessible to a few farmers. The one thing that practically all analysts agree upon is the urgent need to reduce costs, if the program is going to have any opportunity to involve poorer households.

Organic feedstocks

In India these consist primarily of cow dung. The correct social opportunity cost of dung is its value in the best alternative use; this is usually assumed to be as fertilizer. This simplifies the analysis because fertilizer is both an input and output of the system and the costs and benefits largely offset each other.

Bhavani (1976) gave a composite estimate based on uses of dung for both fuel and fertilizer. She concluded that "it is obvious that the whole economics of biogas plants depend on the proportion of cow dung which is used as fertilizer before the introduction of biogas plants". Therefore the price of dung must be taken as fertilizer and as cakes. This assumption does not improve the economics of biogas plants, rather the reverse, for it means that the replacement costs of the biogas plant output should be valued in the same way as the dung input. In practice, most Indian farm households are not able to afford the investment anyway, and for the few that can, the assumption of a market value for dung is reasonable.

Labour time involved in collection of organic materials and water, digester operation and maintenance

Since it is usually assumed that an equal amount of labour is required to collect dung for traditional uses (fuel or manure) as for the biogas plant, frequently no extra value is assigned in financial analysis or labour costs to dung

collection. With the larger farmers who have biogas plants, cow dung is often collected only from the farmyard, and it is more convenient to aggregate this labour requirement with other labour uses. A constant water supply is a requirement which often restricts possible plant locations since many villages do not have adequate year round supplies. The other main tasks are mixing water and dung, feeding the plant, stirring, and spreading an equivalent amount of slurry from the plant onto the compost pit (Berger, 1976 for Nepal and for China, van Buren, 1979). In a social cost-benefit analysis, the labour to run the plant is more plausibly valued at zero in contrast to the labour used in construction.

Maintenance

Poor maintenance has been said to be the single most important cause of plant failure in the digesters' design, particularly the failure to paint the gas holder to avoid corrosion. According to a survey by Moulik et al. (1978) for KVIC system, the major item of expense was the gas holder. Survey evidence suggests that access to technical assistance is a major determinant of plant performance, and yet social benefit-cost studies rarely consider this as a cost item. The development of Biogas Offices for helping the farmers maintain the plants was a key in the special rural development in both China and India. Marchaim, during his tour in China (1990), found that most families expressed their thanks to the extension biogas officers.

Economic evaluations

A consensus on methodology should be developed to allow economic data to be compared among various applications, under varying circumstances, and to enable rigorous economic comparisons between biogas and other renewable energy technologies, or with conventional energy sources.

The financial viability of biogas plants depends on whether output in the form of gas and slurry can substitute for fuels, fertilizers or feeds which were previously purchased with money. If so, the resulting cash savings can be used to repay the capital and maintenance costs, and the plant has a good chance of being financially viable. However, if the output does not generate a cash inflow, or reduce cash outflow, then plants lose financial viability. Finally, if broader social criteria are used to evaluate biogas, conclusions will be more favourable than a strictly financial analysis. Social viability is difficult to evaluate because of problems in valuing secondary benefits.

The financial viability of community scale plant" is limited by similar considerations as household units, although economies of scale will tend to make them a better prospect financially. However, it appears that the primary barriers to diffusion are not economic or technical, but rather social and organizational. Since the benefits from a community plant can be shared by poorer households that would not be able to afford the investment and operating cost of household units, community plants may be more socially viable than the smaller units.

Chapter twelve: Technical and social constraints in integrating biogas plants into farms

[Constraints delaying the diffusion of installations](#)
[Reguirements for an optimally integrated biogas installation](#)
[New incentives to build biogas plants](#)

The number of constructions of agricultural biogas plants in Europe has been steadily decreasing during the last few year. Willinger (1988) tries to point out a few of the major technical, financial and social problems which led to that development. A technical check-up list and some ideas on marketing strategies should help to overcome this bottleneck.

Starting with the first oil crisis in 1973, considerable research efforts in the field of renewable energies have been undertaken all over the world, in particular on the topic of anaerobic digestion. The phase of basic research was subsequently followed by applied and pilot plant research and is at present carried on with demonstration plants. Despite the progress of research and the support of pilot and demonstration plants by the governments and the EC, the technique has not become as widespread in European agriculture as had been hoped. The expectations may have been too high: it took 100 years to replace firewood by coal, and a further 30 years passed before oil became the predominant energy source. Finally, the development of nuclear energy has taken more than 20 years, even though the investments in research were, by the power of three, higher than for anaerobic digestion.

Currently, something over 500 biogas installations are in use on European farms (Demuynck and Nyns 1984). There are many reasons why farmers have constructed these plants. The main incentives include substitution for oil, autonomy in energy, hygiene and odour reduction of the manure, improvement of fertilizer quality, and to protect the environment. Whereas in the first years of the development, the aspect of energy was the major, if the not the only reason to build a biogas unit, in recent years the environmental impact (fertilizer quality, odour reduction) has gained considerable importance. Unfortunately, the rate of construction has slowed down remarkably during recent years. Development has also followed a slow growth rate. The phase of initiation, after the oil crisis, was followed by a fast growth phase, which around 1984, turned into disenchantment, caused by a number of factors.

Constraints delaying the diffusion of installations

General Constraints: Biogas production suffers the drawback of all renewable energy sources: it is a very complex technology, requiring the combination of a variety of classical fields of engineering, i.e. of professionals who by tradition are not accustomed to collaborate. In other words, when it comes to alternative energy, the traditional electric or mechanical engineer is outdated. Unfortunately, this simple remark encompasses the major constraint against a fast diffusion of renewables. At present, there are too many highly trained engineers in the field of nuclear energy.

Technical Constraints: Even under the broadest definitions, the 500 biogas plants described in the EC survey (Demuynck and Nyns 1984) can still be divided into roughly 17 different systems. Particularly during the first years of development, every constructor designed his own biogas system. Hence, the same mistakes have been repeated many times. As a result, many installations have been discarded , but only after they had contributed to a bad image of biogas technology. Nowadays, the technique has become simpler and more efficient. Construction costs could be reduced at slightly higher planning costs. Unfortunately, the market is diminishing, so the dispersion of the better new plants is very restricted. However, there are still possibilities to make designs more sophisticated, with a higher degree of standardization. Progress could be enhanced if public funds were available to support small, but flexible engineering firms, specializing in anaerobic digestion, rather than large offices, which often stick to known but outdated techniques, because of their high overhead costs. In addition, smaller firms are more willing to share knowledge with other groups, which is an obligatory precondition for the fast development of small-scale techniques. As a negative example of misunderstood application of biogas technology, the gigantic MBB-projects in Germany and Asia could be mentioned. But also the often-cited village biogas plants in Denmark still suffer from the narrow thinking typical of large engineering firms. As one of many positive approaches of technical cooperation, the initiative of the Folkecenter in Denmark could be mentioned. Apart from personnel-related problems, there is another major obstacle reducing the diffusion of biogas plants. Only in recent years have liquid manure systems been developed, whereas roughly 80% of all farms have a solid-waste manure system. However, the technology of solid-waste digestion is still based on the batch digester, essentially designed in the 50s. In many cases, another renewable energy source such as wood or straw competes with biogas.

Financial Constraints: The major financial restriction is the price of oil. Until about 1985, most of the biogas plants had pay- back periods of less than 15 years, which was compatible with its life expectation. With the decreasing oil price, however, pay- back periods became almost infinite. Unfortunately, energy costs are always base* of the price of oil, which is not quite correct because the latter does not include social costs. With renewable energies, the cost of reduction in air pollution is actually paid by the owner of the respective device, while future generations will have to pay the price for the current pollution.

An improved basis of costing could be achieved on the basis of the price of electricity, if electricity companies were to pay realistic costs. This means prices reflecting the real energy costs of a newly built power plant. As long as the world market is saturated with cheap electricity, from about 0.04 SFr./kwh), chances are small that higher prices will be reimbursed for electricity from renewable sources, despite the fact that, from the point of view of political economy, the production of electricity from biogas

would be the most favourable solution. The overall process efficiency is high (more than 80%) and the electricity produced has a very high energy capability. Another financial constraint, which affected the development and ultimately the diffusion of biogas plants was the reduction of research money in several countries.

Social Constraints: Certainly, the negative image of biogas production, which was created by the early installations, has considerably reduced the interest of farmers to build biogas plants. In particular, the malfunction of the widely announced, large-scale demonstration units, such as the village biogas plants in Denmark, or the installations erected in agricultural schools in Switzerland, had a detrimental effect on the local diffusion, even though a considerable number of problems arose only from poor maintenance, because nobody felt responsible. Since biogas is a "new" technology, the social pressure to build one's own installation is lacking. Due to the low density there is no feeling of social pressure, nor a pressure from agricultural consultants, because they are not familiar with the technology either.

Biogas still has the "pioneer" image in Europe, instead of carrying prestige. Despite high investment costs, it is considered as low technology, only good for Developing Countries. A professional marketing approach, including advertisement, courses for consultants and engineers, as well as introductory seminars with site visits, for politicians, would probably renew the diffusion of biogas plants. A few approaches are currently under way, but international coordination would certainly speed up the process.

Requirements for an optimally integrated biogas installation

Before any concept of propagation is initiated, one has to make sure that a number of biogas systems are available which can satisfy not only from a purely technical point of view (which has to be proven in practice) but also from the view of an optimal integration of the system into an existing or a new farm.

Figure 12.1 is compiled for the construction of a biogas installation.

Stable Within the barn, the manure removal system is the most crucial point which often leads to operational problems. The design of the manure channels is very important. Their size and the type of the removal device should be coordinated, as several authors have pointed out (e.g. Robertson 1977; Nosal and Steiner 1986). For more diluted materials, gravity systems without mechanical device are to be preferred. Best results have been obtained from sluice-gate slurry channels and overflow slurry channels. Excessive use of water for flushing lead. to a high process-energy demand, and requires higher digester volumes. Whenever slurry channels have to be flushed, fresh or digested manure should be used. The addition of untreated solid waste should be avoided, since it tends to form scum. Chopping of long straw, in the liquid phase, requires more energy than shredding before bedding. Reception pits should be placed within the barn, if possible, or should be insulated, to minimize heat loss from the manure. Their volume should be as small as possible. One should be aware that for every degree Celsius lost per m of manure, on the way to the digester, about 260 1 of biogas have to be invested, to recover

the temperature.

Figure 12.1: Compiled for the construction of a biogas installation.

Process Parameters With mesophilic digestion, HRT should be as short as possible. Best yields were achieved at 10 - 15 days with piggery waste (Van Velsen 1981), at 10 days with waste from fattening cattle (Baserga 1984) and at 18 days with straw containing cow manure (Wellinger 1985). However, recent developments have shown that in cold climates, the best net energy yields were achieved at HRTs of 40 - 50 days and a fermentation temperature around 22°C (Sutter and Wellinger 1987). For countries which require, by law, long storage capacities of manure, such as Germany or Switzerland, a combined system for storage and digestion (ACF-System, Wellinger 1988) brought excellent results.

Design Criteria. Whenever possible, sunken digesters should be built. They do not need pumping, either from the barn into the digester, or from the digester into the storage tank. The investment cost for pumps is low, but their lifetime is very short, and replacement costs are high. With a direct flow from the barn into the digester, an important amount of heat in the fresh manure can be conserved. In addition, sunken digesters have considerably lower heat losses in winter. However, in the majority of cases the digester has to be erected above ground. Good insulation, preferably on the outside of the digester, with a thickness of 12 cm or more, yielding a U-value of 0.4 W/m3.K or less, is strongly recommended.

Heating systems are preferably built of plastic materials, in order to prevent corrosion by differences in galvanic potential. Optimal performances vary from 150 W/m^3 to 270 W/m^3 of digester volume in function of TS-content and HRT (Walther 1985). To avoid crusting of the heat exchangers, the water temperature should not exceed 55°C. For mixing, the best results were obtained from slow rotation stirrers (5 - 25 rpm), which provide enough motion to keep a possible scum moistened, and prevent the formation of a heavy sediments. Good stirring can be achieved with mixing powers of 25 40 W/m^3 digester volume, and an energy input of more than 40 W/m^3 /d. If straw or other bulky material is fed, stirring alone can not prevent scum formation, as long as the scum- forming material is not removed (Baserga et al. 1985). Another way of stirring the mass inside the digester is by circulating the biogas through the slurry. This has been done for many years in the anaerobic digestion of sewage, and is therefore a proven technology.

Gas Utilization. The possibilities of biogas utilization are the same as for natural gas. In an optimally-designed installation, the gas produced is utilized close to 100% all year round. This is the only way to achieve economical operation. The gas produced should therefore cover the base-line energy demand, while the peaks are covered with a different energy source, such as wood or straw. If the peak energy has to be combined with biogas, in many cases hot water storage is the energy-store to be compared with other types of gas storage. For most electrical applications, desulphurization of the gas is recommended (Egger 1984). The removal of carbon dioxide however, is not necessary, even when the gas is compressed (Wellinger et a]. 1984).

If all factors for optimal integration are carefully evaluated, the running costs of an installation will

automatically be as low as possible.

New incentives to build biogas plants

During recent years, the construction of new biogas plants has continuously decreased, but there are signs that this trend has bottomed out. Increasing environmental problems and air pollution catastrophes in recent years, leading to increased diseases of the respiratory organs, and to dying forests, have led to considerable changes in public opinion. In several countries, virtually no new community project is accepted (energy concepts, waste disposal, constructions of public buildings, etc.) where not at least one possibility of alternative energy application has been studied. If this new social pressure continues, it will bring with it new motivation for the farmer. But even more important, a number of new laws on energy consumption and environmental control have been introduced and accepted, which, before long, will also bring better financial support for the application of renewable energies, in the form of subsidies or tax reductions.

If we now seize the opportunity of the positive social and political atmosphere, and succeed in pushing through the construction of a significant number of efficient biogas plants, either in industry or agriculture , we may well see a break- through of anaerobic digestion, independent of the present price.

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Chapter thirteen: Biogas programs in developing countries

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Most countries became aware of biogas technology by the middle of the Twentieth Century. However,

real interest in biogas was aroused from 1973 onwards, with the onset of the energy crisis, which drew general attention to the depletion of fossil fuel, energy resources and the need to develop renewable sources of energy, such as biogas. The importance of biogas as an efficient, non-polluting energy source is now well recognized.

International organizations like the Economic and Social Commission for Asia and the Pacific (ESCAP), the Food and Agriculture Organization of the United Nations (FAO), the United Nations Industrial Development Organization (UNIDO), the World Health Organization (WHO) and the United Nations Environment Program (UNEP) have done considerable work in disseminating and developing biogas technology

Afghanistan Biogas development has been initiated through a UNDP- supported biogas demonstration project. It has been proposed that demonstration plants be set up in each agro-ecological zone. Based on the experience obtained with the demonstration projects, extension programs will be undertaken.

Bangladesh Although research and development work on biogas has been undertaken since 1973 by the Agricultural Universities, little headway has been made in implementation of the programme at the field level. A few demonstration plants have been installed. Bangladesh Agricultural University organized a training course at Mymensingh during 1981 with the assistance of UNESCO. Many of the plants so far set up are of KVIC design. However, experiments are being carried with fixed dome models. A comprehensive developmental plan, which would involve UNEP assistance, has been drawn up, in view of the urgent need to replace firewood as fuel.

Bhutan The first large-scale program was begun in 1987, through cooperation between UNICEF and the Rural Energy Division. Fifty- four 2 m^3 and 3 m^3 fixed dome digesters were built in 1988 and are functioning satisfactorily.

Burma (Union of Myanmar) Even though Burma is self-sufficient in fossil fuel and firewood resources, deforestation, inadequate transportation infrastructure in certain areas, and the anticipated increase in the demand of energy sources have necessitated taking up measures for the development of alternative and renewable fuel energy sources. Research on various aspects of biogas technology has been conducted by the Central Research Organization for the last 10 years. The Agriculture Mechanization Department of the Ministry of Agriculture and Forestry is one of the main institutions involved in the development of a programme. The Department has developed a semi-industrial type biogas digester with a m capacity of 50 1/day. In 1981 six continuous floating drum type digesters were constructed on cooperative and meat producing farms. About 40 floating drum digesters were constructed in 1982 in model village No. 1, near Rangoon. The Biogas Production and Utilization Centre was established under the Ministry of Agriculture and Forestry in 1983 to coordinate research and implementation of biogas technology. It is planned to cover 500 villages in 10 states under the biogas development project.

The target of 2000 family units was set in 1990, for which 14 construction teams (one for each State or

Division) are available.

China China has a total area of about 9.6 million km^2 and a total population of 1.100 million. The population growth rate is at about 1% per year. There are about 900 millions peasants in rural areas and some 60% of the total population is engaged in agriculture. About 34%. of the total area is under cultivation. The forest area is about 14%. During the last two decades, the forest area has been increased by 11 million ha.

There are about 130 million cattle and draft animals, 260 million pigs, 170 million sheep and goats and some 1,400 million poultry in China. The farmers keep on Average 0.3 cattle units (500 kg live weight) per ha. Energy consumption in 1984, in rural areas, was some 370 million tons Coal Equivalents, around 40% from coal and 60% from biomass (straw and firewood). This corresponds to 230 million tonnes of straw and 180 million tonnes of firewood. Another estimate gives a consumption of 400 million tonnes crop stalks and straw, burned annually as domestic fuel. It accounts to some 80% of rural domestic energy consumption. In addition, 70 million m firewood is burned annually. The productivity of woods and forests is 120 million tonnes firewood only, leaving a deficit of 60 million tonnes annually.

Experience with biogas in China

China has learned many lessons during the recent past. After 1975, slogans such as "do it in a big way" or "biogas for every household" led to the construction of 1.6 million digesters annually, which were very cheap (Yuan 20 - 30) but of low quality. In 1980, over 50% of all digesters were found to be defective and were not in use. The consequence was that in 1979, the policy was changed to "strengthen leadership, popularize positively, develop in a batch way, advance steadily". Construction activity slowed down to less than 1/3 of the previous one. Attention was paid to combine quantity with quality to reach a consolidated development. In this period, 95% of all digesters constructed were flawless and the utilization rate was above 85%. The measures now have to be matched to the local conditions. Climatic as well as social and cultural conditions are being studied first before digesters are being introduced. Not all places are suitable for biogas. In the Sichuan Province, digesters are constructed mainly in those areas where there are no small power stations, coalpits or possibilities for planting fuel wood. It was also learned that the popularization of BG would only be successful when the direct benefits to the farmers are obvious. To raise the direct benefits, PBTs help in comprehensive utilization of residues. Thus, a digester is the key to integrated farming systems. People recognized that management is the key to success because the development of BGT in the long term. There are many management tasks to be done in preparation, construction and operation of digesters (policy development, proper design, organization and financing of training and extension services, material supply, rewarding etc.). The rapid economic development in rural areas has brought along some new problems to the biogas extension work. More and more coal pits have been set up, while rice yield, and thus straw harvests, increased also. The peasants are not so eager any more to construct digesters because of easy access to coal. More and more peasants set up small individual enterprises, abandoned farming, and thus lost the prerequisite

for a digester. Additionally, market prices for e.g. cement increased and part of the cement has to be purchased from the market. Not all farmers can be supplied with levied cement. Although quality of digesters and benefits of operation have been improved greatly in recent years, the speed of development is low.

Potential of biogas generation and biogas digester construction

Chinese peasants use a wide variety of substrates, such as straw, night soil and, manures as a substrate for the biogas process. Different sources estimate that the total potential of biogas plant is from 145,000 - 62,000 million m^3 biogas (45% from animal manures, 5% from night soil and 50% from straw and stalks). This would be equivalent to the total energy demand of rural households for cooking and lighting. Only 2.5% of this potential is actually being produced by about 9/million digesters today. Gas production ranges from 0.20 - 0.25 m^3/kg TS, or 0.1 - 0.15 m^3 /d. In rural areas, where water is scarce, or where people are used to handling dry manure, the dry-fermentation technique is popular. Preparation of feedstock differs slightly. The gas production is above 0.2 m^3 / per kg TS added, and 0.2. m^3 per day.

The total potential for biogas plants may be compute] from the potential of biogas divided by annual production of 300 m gas, which results in some 200 million digesters. At the current construction rate of about 500,000 digesters per year, it would take more than 400 years to exhaust the market. For the time being, biogas plants have been constructed in 16 out of 28 provinces. The climatic conditions in the other provinces are less favourable, and the impact on the total potential for digester construction would still have to be assessed. The purchasing power of farmers seems to have only a small influence.

At present, there are about 5 millions family sized fixed dome plants of 6, 8 and 10 m volume operating in China, 50,000 red-mud-plastic (RMP) digesters of over 10 m^3 and the target is 400,000 - 500,000 of the small household digesters and 25,000 for medium and large-scale (farms, distilleries etc.) annually. Even though China has the largest construction rate of all countries in the region, it is slow compared to the huge potential. The new attitude is to develop positively, pay attention to both construction and especially to management, and to seek practical benefits. Sound work and quality in construction are emphasized. Construction of family-sized fixed dome digesters is well advanced, and already standardized at national level. Sound experience is available regarding properties of construction materials, technique and design. Construction material and technique are selected at the site (e.g. brickwork, lime-mortar, cement-mortar, concrete cast-in-place etc.) to keep costs low.

Biogas utilization

The gas is used by about 25 million people for cooking and lightning, for 8 - 10 months a year. Many

rural households are equipped with both bilgas stoves and improved cooking stoves. With the latter type, the peasants burn straw and wood as usual during the winter months for cooking and heating. Improved and cheap biogas stoves and lamps have been developed, and are distributed to every biogas owner. The cost of one biogas lamp varies between 6 12 Yuan. Lamps and burners are adapted to low pressures of about 2 cm, at which RPM digesters operate. Commercial and industrial burners are also being investigated in China. Furthermore, the use of biogas is manifold: there are about 400 biogas power stations, with a total capacity of 5,800 HP. 800 biogas electric stations, with a total capacity of 7,800 kw, provide electricity to over 17,000 households. Thus, China has solid experience in running diesel and gasoline engines with biogas.

There are numerous agricultural applications, such as crop drying, tea baking, egg hatching, cultivation of rice seedlings and mushrooms, etc. Catalytic infrared radiators, hatcheries, refrigerators and air conditioners with automatic control have been developed and are used.

Effluent utilization

Whether the biogas plant of the anaerobic process can survive depends on its benefits over and above the biogas produced, especially on its comprehensive benefits. Benefits from effluent have been given high priority in China and the utilization of residues has a bright future. Through the digestion of straw, a high amount of fertilizer is conserved in China. More than 90% of N. P. and K are located in the sludge of digested manure.

The residues are used in agriculture, aquaculture, for growing edible fungi and for raising earthworms. Top dressing is recommended in some provinces. The yield increase of crops was found to be higher using digested slurry than with chemical fertilizer alone. Soil fertility (stable humus) increased, as well as soil porosity and water retention capacity. Rice yields increased by 11 - 14% compared with control. Fish yields were 25% - 50% higher than when fed with pig manure directly. Mushrooms could be picked 3-7 days earlier and the yield increased by 6%. The residues after mushroom cultivation still has fertilizer value. It is estimated that every 8 m biogas plant can provide the medium needed for 55 m of mushroom culture. Raising earthworms is becoming popular in China. For example, there are 550 specialized households engaged in earthworm raising in Jiangsu Province.

Various kinds of equipment are used to remove the slurry from the digester, to transport it to the fields and to apply it. This is done about twice a year, after the wheat harvest and the rice harvest. According to the different fermentation methods, the residues have different total solids contents, and are adapted to the local customs of application of organic manure.

Economic aspects

Construction costs vary by about +100% depending upon the location. In recent years, prices have increased considerably: from 1983 - 1986, the price for cement increased from 40 Y/t - 100 Y/t, for steel from 500 Y/t - 1,100 Y/t, and for sand from 15 Y/m^3 - 20 Y/m^3 . The price for gasoline is now 1.1 Y/l, for diesel 0.5 Y/l, and for electricity 0.15 Y/kWh. Today, a farmer has to invest 250-300 Yuan for a 6 m^3 digester, with a service life of about 20 years. At this size, the cost per digester volume is about 42 - 50 Y/m^3 or about US\$ 12/m^3. There is an economy of scale effect, i.e. each m of larger digesters becomes cheaper to construct. The construction charge is about 40 Yuan (4 Yuan per man and day). Thus, the labor charge contributes only a small fraction of the total cost and in many villages the farmer can construct the digester by himself, with the instruction of the people from BGT offices. There is a guarantee for quality, over a 5 year operation period.

Financial support

The policy of the Chinese Government is "emulating through consolidation, developing positively, paying attention to both construction and management, hence seeking for practical benefits" and the principle of "taking construction by farmers themselves as a mainline, and state and collective support as an aid". The Biogas Service Companies (BSCS) have, in general, to rely on themselves, and near and around cities profits are possible. Those companies without profit will receive subsidies from the County Government, which has special funds for extension, development and demonstration at its disposal for community digesters. In Chungdu County, BSCs receive Yuan 20,000 - 60,000 regularly as a subsidy. The investment provided by the Central and Local Governments on biogas construction is several tens of million Yuan per year. In the Sichuan Province for example, the Government allocated Yuan 49 million for the development of biogas from 1973 - 1984. A considerable sum of investment comes from collective economic organizations in the countryside. Low interest or State subsidized loans have been given by the agriculture bank to the farmers who have difficulties building digesters. Several BGT people at the Biogas Service Office in Chengdu install Biogas plants in Ta Xin Township and other places: the work of the Office has been profitable enough to enable them to buy a restaurant nearby with the money earned from building improved septic systems in many dormitories around Chengdu.

Special support is provided to community digesters. One important example is the plant near Shenyang. The total cost in 1983/84 was 260,000 Yuan, and 80,000 Yuan of it were spent on 5,200 m of gas pipes. The main pipe has a diameters of 17 cm. The income is 60,000 Yuan per year and the calculated payback period is 6 - 7 years. It would be even much shorter if the distillery would have replaced all its fuel consumption, because the price for industrial coal is twice of domestic coal. Under this condition, the subsidy of 50% by the local Government and 25% of the village Government would not have been approved. Thus, the 400 villagers only paid 25% of the investment, about 100 - 200 Yuan per family. A connection to the natural gas pipeline system would require an investment of Yuan 1,600 per family. In the Chengdu vicinity, a poultry farm where BRTC has built a demonstration digestion system (2 x 50 m^3) in a family-owned chicken farm with 20,000 layers exists. The family invested Yuan 40,000 in the

system, in addition to the subsidy they received from the government. The biogas is used for cooking, lighting and to heat the hatchery. The digested slurry is used in part for the fish pond, and the rest is given to farmers as organic fertilizer.

Training in biogas technology

Training courses at the highest level are conducted at BRTC in Chengdu since 1981, for staff members of Biogas Offices, up to provincial level. 2 - 3 courses are given each year, with 50 participants in each course. The duration is 50 days per course. Training comprises "training of trainers" and of "workmen". More than 1,000 people have been trained. Workmen are responsible for extension and organization of development work, and for information and management. Technicians will become trainers in Biogas Offices. Biogas Offices at (and above) County level hold courses for 30 - 60 days. After that, the trainees have to join a Construction Team for half a year. These trainees will later work in other Construction Teams. Peasant Biogas Technicians (PBT) receive a theoretical training of 30 days only and a shorter practical training. All technicians receive Biogas Technician Certificates when they passed the examination. Training in new technologies has also regularly been given to PBTs who already got their certificates. In the Sichuan Province, 200,000 peasants and cadres have received basic training since 1973. 6,000 PBTs are now working in the countryside.

Bio-energy and rural energy is taught as specific subjects in 4 colleges and 4 specific middle schools. The Department of News and Propaganda (radio, TV, newspapers, magazines) is spreading information and thus training at a popular level.

Moreover, the BRTC in Chengdu gives international training courses. Since 1982, 5 courses with 98 participants from 38 countries have been held. Most of these participants, who have been trained for 4 to 6 weeks, play an active role in BGT in their home countries. The development of scientific research in BGT has enhanced extension and dissemination. Intensive research has been done on construction and on design (application of technology), in which 13 organizations were involved. Current activities focus on design of medium and large scale digesters (100 - 500 m volume). The Chinese Academy of Science is also involved in R & D projects. Other areas of research are on:

> (a) fermentation techniques;
> (b) comprehensive utilization of biogas and residues;
> (c) new materials (RMP);
> (d) basic theories on BGT;
> (e) gas utilization.

Organization of the biogas sector

Construction of the digester is the basis, while management is the key to Biogas development. The great attention and strong support by the Chinese Government are the key factors for rapid biogas development in China. The overall coordination is under the direction of the State Science and Technology Commission (SSTC) and the Ministry of Agriculture, Animal Husbandry and Fisheries (MAAHF). This is shown in Figure 13.1 below. Some 100,000 people work in the whole scheme of biogas technology (BGT). The SSTC itself has 14 Departments, with 400 staff members and 17 affiliated organizations with 4,600 staff members. Two of the departments are concerned with energy: the Department for Industrial Technology (BIT) and the Department for Scientific and Technological Information (DSIT). Energy is one of 5 fields of activity at DIT, and is subdivided into Conventional, New and Renewables Sources of Energy. The functions of this Division are policy and legislation, planning, management, information and international cooperation. Among the affiliated organizations, the ISTIC (Institute of Science and Technical Information of China) and "Chonquing Branch, Institute of Scientific and Technical Information of China" are engaged in BGT. The Science and Technology Commission has offices at Provincial and Municipal Level. It maintains Municipal and local research institutions. All research institutes were set up recently (1984-85). The "Liaoning Province Research Institute of Energy Resources" (LPRIER) was set up in 1985. It is to develop, demonstrate and extend new sources of energy: Solar (PV and thermal), Biogas (semi plastic or red mud plastic (RMP) and industrial plants) and Fuel Alcohol (from sweet sorghum). The organizational chart is given in Figure 13.2 below.

Figure 13.1: Chart on overall organization of the biogas field in China

Figure 13.2: Organization chart of "Livening Province Research Institute of Energy Resources" (LPRIER)

It is associated with three other institutions. All together there is a staff of 130 people, with over 70 people with technical qualifications. Biogas research is conducted for processes at industrial scale (distilleries). The institute also assists the activities in dissemination of RMP digesters (semiplastic digesters) of the associated institutions. The main activity, however, is R & D into equipment and its dissemination, to make use of solar energy. The institute is highly interested in giving international courses and seminars on new and renewable sources of energy.

The MAAHF is in charge of training, dissemination, extension and applied research on Biogas technology.

Biogas Offices (BO) are in charge of management, of training, of construction (selling building materials) and of extension. Biogas Service Companies (BSC) consist of qualified construction teams, with varying numbers of technicians and work under the leadership of the BO

BOs at and above County level are authorized to train technicians. By the end of 1984, there were 25 BOs at provincial and, municipal level, 592 BSCs above County level, 1,240 BSCs (stations), and

numbers are growing with the population of the biogas technology. below village level, 8,854 construction teams total staff of 10,000 and 40,000 peasant biogas technicians (PBTs). Municipal Biogas Offices are responsible for cities, and construct digesters to treat night soil, slaughter house wastes, distillery wastes, dairy farm manure etc. Country level BOs are responsible for about 10 townships. Each township has about 50 villages with about 10 teams. There are about 70 families, with 3 - 4 members per team. Bach team has its own Peasant Biogas Technician (PBT), who takes care of repair and maintenance of digesters. He may construct digesters as well. The relationships such men have with the farmers is what enables the whole system to work.

Research and training at National level is conducted by the Biogas Research Institute in Chengdu, Sichuan Province. This Institute was established in 1979 with the approval of the State Council. To date, the Chinese Government has invested more than Yuan 10 millions. The annual budget is about Yuan 700,000. UNDP has provided equipment for over US$ 400,000. The Institute has a total of 150 members, of which 100 researchers are at college level, with 19 different professional qualifications.

Since 1982, 5 international Training Courses, with over 100 participants from 40 countries, have been held. This activity was sponsored by UNDP and FAO, the first course also by ESCAP. Since 1981, 12 national training courses have been held with more than 1,000 participants. Thus, the BRTC institute plays an active role in national and international development and implementation of Biogas Technology.

The main tasks of the BRTC Institute and Centre are:

> (a) To undertake research on BGT and use of biogas for rural agricultural development and other fields, in order to provide cheap energy for peasants;
> (b) To coordinate concerned United Nation Organizations for international biogas courses, and especially to train technicians in Asia and the Pacific;
> (c) To collect information, disseminate and publish (China Biogas Quarterly), in order to serve as a centre for Biogas Information Network and publish the academic journal "China Biogas" in coordination with the China Biogas Association;
> (d) Design and construction of medium and large size plants in China and abroad (distilleries, large farms systems and sewage treatment) and the coordination and control of national R & D in BGT.

The chart in Figure 13.3 gives an overview on the structure of the China Biogas Research and Training Centre Institute (BRTC), which is to conduct international training courses and uses the existing facilities.

Figure 13.3: Organization chart of the Biogas Scientific Research Institute and Associated Institutions

Today, there are more than 60 research institutes, universities and 60 local biogas experimental stations in China, with over 1,000 research staff involved in Biogas research. The number of people involved in

BG extension work amounts to about 10,000 people. Thus, a biogas management system has been formed nationwide .

Marchaim, in his recent trip to China in (November 1990), visited a Regional Biogas Office of Nanjing suburban area. It has burners and equipment needed for biogas utilization and a staff of 4 people to serve the region. He found that they are very well acquainted with the technology and have good relations with every farmer in the region who has a biogas system, adjoining the pig pen and the adjacent latrine. Much attention is paid to direct and indirect benefits. They, too, estimated that the indirect (social) benef its are 3 times higher than the direct ones.

India India has a total population of about 800 million people, of whom 80% live in rural areas in some 576,000 villages. About 70% of them are landless. There are about 237 million head of cattle, under the ownership of approximately 52 million households: of these, 57% own 1 - 3 head of cattle, 27% own 4 - 6 head, 8.7% own 7 - 9 head and 6% own above this number.

According to rough estimates, 50% of India's total energy comes from non- commercial sources, upon which the majority of the rural population survives. These include: firewood (65%), dung cakes (15%) and agricultural wastes (20%). On average, these items cover 84% of rural household energy requirements (Maulik 1982). Between one third and a half of all recoverable cattle dung is burned as fuel. The annual requirement for firewood has been estimated as 133 tonnes. Total annual production (from recorded sources) is 49 million tonnes, leaving an annual deficit of 84 million tonnes (Vimal 1985).

Potential for biogas generation and digester construction

The only fuel available for family-sized digesters is cattle dung. This facilitates the assessment of potential, but on the other hand, it restricts the use of biogas to cattle-owners . the assumption that 4 head of cattle are required to generate 2 m^3 gas (the cooking needs of a rural family of 8), there is a potential for 22 million digesters, though when cost to the family is taken into consideration, the maximum potential is 10 million plants, representing 19% of cattle-owning families. Given an average capacity of 4 m^3 gas per day, 40 million m^3 could be generated daily. This would involve about 71 million head of cattle (10 kg dung per day, 20% or 0,28 m^3 gas per kg total solids, about 30% of India's total cattle population.

Latest estimates by the Advisory Board on Energy give a figure of 16 - 22 million small biogas units in the country, on the assumption that 75% of all manure is available (Khandelwal and Mahdi 1986).

Experience with biogas in India

Activities have gained momentum since NPBD was launched in 1981 and DNES in 1982. Today, it is generally accepted among richer farmers that a biogas plant is desirable. The earlier period was taken up with problems, such as convincing bankers to give loans and setting up the organizational structure, subsidy system, etc.

Problems which arose can be classified as follows:

(a) design faults;
(b) construction faults (unskilled builders or poor materials;
(c) difficulties of financing (obtaining bank loans and delays in subsidy payment);
(d) operational problems due to incorrect feeding (often the result of over-sized digesters, a status symbol) or poor maintenance;
(e) organizational problems arising from the differences of approach and lack of coordination at the three levels of agency.

Lack of monitoring and surveys may lead to problems in the future. Alternative fuels to cattle dung must be found. The tendency to buy oversized digesters as a status symbol reduces the gain to the user. It is clear that benefits derived from the effluent are 2 - 3 times higher than the direct benefits of biogas, though this and other points are assumptions that are not backed by proper research.

Biogas plants

Up to 1986, a total of 642,900 digesters had been built: in 1985/6 alone, the total was 185,800. In view of the huge potential, targets have been gradually increased. Construction capacity almost doubles each year. At the current capacity, it would still take 50 years to saturate the market. However, this biogas programme, together with others (e.g. wood-saving stoves) has to compete with the pace of deforestation and other environmental hazards.

Community and Institutional Biogas Plants (IBP) are being constructed in India. Poor farmers and low castes are supposed to be involved and to participate in operation of Community Plants (CBP).

Biogas production

In order to adapt KVIC digesters to the various ambient temperatures, from south to north, they are designed for three different retention times to produce the same volume of gas. For the Janata type, this

adaptation has yet to be approved by DNES. There are no long-term comparative tests on gas production of the two models.

Use of biogas

The gas is commonly used for cooking and lighting. There are a number of enterprises in each State that produce stoves and lamps. At some CPBs and IBPs biogas operates engines or agricultural equipment. Only three enterprises in India manufacture or adapt diesel engines.

Utilization of effluent

The effluent is usually dried in the sun, either separately or in combination with agricultural wastes. Partial composting is performed, after which it is applied to the fields in a solid state. There is no information on how widespread the use of effluent is, how it is applied or in what quantities.

A study comparing its use with that of fresh dung, for various purposes, has been undertaken (Myles 1985), basing values on average prices as of October 1985. It was found that the sale value of digested spent slurry, scientifically composted, is 8 times higher than that of fresh manure sold to the owner of a digester.

Cost of installation

Cost of installation varies according to type and size of the plant, increasing by about 65% between 1981 and 1986, or about 13% per year. There are also variations from State to State and District to District. There is an effect of economy of scale in both digester types. A comparison of cost may be made on the basis of cost per m of digester volume. For the same hydraulic retention time (HRT), the Janata plants are cheaper by 33% or more than KVIC digesters. The system of financial assistance is discussed below.

Annual costs and savings

Annual costs though depreciation, interest on loans, maintenance, repairs, overheads and labor costs have been calculated comparatively for digesters of 2 m gas/day for KVIC and Janata models (Myles 1985). In the first 5 years, annual costs amount to Rs 2,480 for a KVIC model at 40 days HRT, and Rs

1,770 for a Janata plant at the same HRT, the latter model costing Rs 1,920 for the 55 days HRT type. On the other hand, annual savings through replacement of kerosene by biogas, and fertilizer by composted effluent, yield a marginal annual gain in the first 5 years. Thereafter income and profit are dubious: first, calculations are made on the assumption that kerosene is used as fuel, when wood is more common, and secondly, there is a tendency to buy digesters larger than necessary. Furthermore, figures on income and profit are based on the subsidy given to the farmers.

Financial assistance from government

At present, DNES provides financial assistance to:

      (a) purchaser's subsidy;
      (b) service charge to State Governments and the KVIC;
      (c) turnkey construction fee;
      (d) incentives to promoters;
      (e) training programs;
      (f) repair of plants with structural problems.

Total governmental expenditure in 1985/6 was Rs. 6,7 million (75% subsidies, 25% training) though less was budgeted for the following year.

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Organization of the biogas sector

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India's "National Project on Biogas Development" (NPBD) for mass diffusion of digesters was launched at the end of 1981, using a "multi-agency, multi-model" approach. The programme is centrally administered by the Department of Non-Conventional Energy Sources (DNES), within the Ministry of Energy. DNES is responsible for the coordination of implementation and R & D of family-sized and community biogas digesters. It has to approve designs and to allocate budgets for training and subsidies. At State, District, Block and Village levels, staff is provided for the biogas scheme as shown in Table 13.4, though not in all cases is the scheme fully staffed.

At State level, the organization is called "Biogas Cell". 14 States, with a target of 10,000 digesters, are supposed to have a staff of 6, the remaining States a staff of 2. 25 central departments in as many States have been set up, and others in a selected 100 Districts. In other Districts, State Governments have either set up such cells under the State Plan sector, or involved staff of allied schemes, e.g. minor irrigation programs (Khandelwal and Mahdi 1986). The broad terms of reference of the Biogas Cell attached to the central department in each State Government includes:

> (a) Overall planning of the execution of the programme in the State;
> (b) State-level coordination of different departments/agencies;
> (c) Institutional financing;
> (d) Arrangements for raw materials;
> (e) Appointment of executive agencies and demarcation of areas;
> (f) Monitoring of programme and the submission of progress reports to the Government of India; (g) Maintenance of subsidy accounts and the submission of expenditure reports the Central Government.

Agencies vary at State level: they may be State Department of Agriculture, Agro-Industries Corporation, or State Department of Non-Conventional Energy, etc. They have varying levels of involvement in extending technology.

At District level, the executive agencies are governmental: Khadi and Village Industries Commission (KVIC) and Action for Food Production (AFPRO). This multi-agency approach is necessary if targets are to be met. The construction of 20,000 digesters annually is channelled through KVIC (1985-6 target). Since starting in 1974, they have constructed 161,000 floating drum digesters. KVIC has a technical staff of 300 (1 Director, 2 Assistant Directors, 40 Development Officers, 100 Assistant Development Officers and 160 Supervisors. In addition, many individual workshops have been recognized by KVIC.

AFPRO coordinates a network of NGOs at grassroots level, using the fixed dome digester (the Janata Model) exclusively (janata = people). AFPRO concerns itself with institution building, placing emphasis on the organization of many training courses in rural area, by competent NGOs. AFPRO has planned and initiated action to develop 80 - 100 Biogas Extension Centres (BEC), involving 60 - 100 NGOs. To date, 60 NGOs, with 90 such centres have been developed, and are involved in construction activity. Their total construction capacity is about 9,000 digesters per year. Most of these NGOs, like AFPRO, promote several rural technologies, biogas among them. Each BEC is capable of constructing 100 biogas plants per year, as well as providing regular after-construction services to plant owners. Each BEC would have a staff of one supervisor and a master builder. The former has the task of education and motivation of farmers, collection and processing of applications, levying cement and other materials, supervision and coordination. The latter acts as leader of the construction teams, professional rural builders hired by the farmers at daily rates. AFPRO has raised overseas funds (the Canadian Hunger Foundation) to support 80 - 100

BECs over a 3 - 5 year period. It is expected that, after this initial support each centre will be self-sufficient.

Table 13.4 : Organization Structure (India)

No.	Level	Coordinating agencies staff	
19	State	14 States:	1 Joint Director, 1 Sr. Agric. Officer 1 Accountant, 1 U.D.C. 1 Secretary 1 Sr. Agric. Officer 1 U.D.C. Nat. Bank for Agric & Rural Development
		5 States:	
		All States:	
112	District		1 Block Dev. Officer 1 Supervisor, 5 Techs.
50-60 per			
District	Block		5-10 Rural Welfare
			Officers
30 - 100 per			
Block	Village		Village Level Workers

Sources: Mahdi, S.S. (1982). Khandelwal, K.C. and Mahdi, S.S. (1986).

Indonesia The biogas development programme in Indonesia is in the initial stages. Only a small number of plants exist, the reason being that firewood is plentifully available in most areas.

The Bandung Institute of Technology, its Bogor Biological Institute and other governmental institutions are engaged in research and development work. Efforts are being made to evolve an efficient model through suitable modification of existing Indonesian and Chinese designs.

Some demonstration units have been set up at places like Denpasar, Petung, Atuag, Bogor, Baruajak and Bah. The units are made of oil drums with floating gas holders. There is opposition to the use of pig dung as a feed stock by the Muslim population.

The Indonesian Board of Voluntary Services is promoting the biogas programme by putting on demonstrations at the village level to convince villagers and village leaders. The Bogor Biological Institute is also launching a biogas programme based on the use of agricultural wastes as a feedstock.

In 1981 the FAO/TCP biogas project was initiated in Indonesia with the objective of setting up a few demonstration units, providing training and preparing a comprehensive programme for incorporation of biogas technology in the integrated rural development programme. The Government is planning to formulate a national biogas development programme, with Bali as the focal development centre.

Iran The Centre for Endogenous Development Studies is engaged in propagating a biogas development programme in western Iran. Trials are being carried out at Niazabad with KVIC-design plants.

Israel The Israeli project on the utilization of agricultural wastes was based from the beginning on the integrated approach (Rousseau et al, 1979), employing economic evaluation studies, and tailored to differently structured farms. The biogas produced during the anaerobic digestion is only one of several products.

Several institutes and commercial companies are involved in developing anaerobic digestion of organic wastes in Israel. Only a few large scale commercial systems and demonstration systems of 200 m have been built in Israel and two other countries, based on the "Nefah" technique. Methanogenic Thermophilic Anaerobic Digestion was selected to treat manures and slaughterhouse wastes of high solid contents (over 15% dry matter). Economic evaluation studies in Israeli Kibbutzim, with feedlots and over 300 milking cows per cowbarn, showed the benefits of the treatment of the high solid content material. The thermophilic temperature ($55°C$) changes the viscosity and allows treatment of the wastes. A higher digestion rates is achieved as well as eliminating Salmonellae and reducing other pathogenic bacteria populations. As evident from the experiments, done in Israel and other countries, there is a reduction of several orders of magnitude in coliform bacteria and in most cases total elimination of Salmonellae. An integrated commercial system has been developed that solves ecological problems in an economic way by Methanogenic Thermophilic Anaerobic Digestion (MTAD). The products of the system are Biogas and a peatmoss substitute for the greenhouse and mushroom industry. In addition, a liquid fraction is produced, used as a fertilizer. The process simultaneously reduced BOD and COD and is effective against pathogenic bacteria. The main saleable product of the process is a substitute for sphagnum peatmoss (called Cabutz or Peatrum), which was examined as a casing-soil substitute for growing Champignon mushrooms, and is also used commercially in Israel as growth medium for pot-plants. This material was produced from the digested slurry by separation on a vibrating screen and the fibrous peat-like material which was obtained by sieving and leaching was tested for its physical and chemical properties. It was found to maintain high hydraulic conductivity and air capacity, as well as adequate water and nutrients retention, like peat-moss, as was shown for digested slurry from cow manure (Marchaim, 1983).

This Israeli MTAD process works at the highest possible organic loading of the wastes collected, since economic evaluation showed that the higher solids content in the added material is important if a profit from the anaerobic digestion plant is to be achieved. MTAD was demonstrated not only as a process which converted part of this material into useful substances, but also as a decontamination process. The process is used to treat manures, rumen content from slaughterhouses and other agro-industrial wastes, e.g. instant coffee waste.

Japan In Japan, anaerobic fermentation research and development was viewed more as an anti-pollution measure, rather than as an energy alternative. Since 1973, nationwide efforts have been made to reduce pollution problems resulting from animal, human and industrial wastes. Several institutions like the National Institute of Animal Industry, Chiba, the Public Works Research Institutes, Fermentation Research Institute, Inage, Hitachi Plant Construction, the Ministry of Agriculture, and the Agency for Industrial Science and Technology have been working on anaerobic fermentation of organic wastes.

Big digesters to treat industrial wastes, particularly from alcohol distilleries have been set up. High temperature digestion in thermophilic range, especially for industrial wastes, is being adopted. There are no differences in the quantity of gas produced in thermophilic and mesophilic digestion procedures. However, thermophilic digestion has the advantage that it allows for the reduction of the retention period to five-seven days and makes possible higher loading rates (2.5 times), thus increasing the scope for reduction in digester size.

In 1974, the Sun Shine Project was initiated with the objective of developing new energy technology. Among other

subjects the Project includes investigations into anaerobic digestion of animal, human and solid urban wastes. Interest in small digesters has again been renewed. Small digesters, using a steel tank with an agitator and a water coil for heating the slurry, have been developed. The digester has a double wall for insulation against low temperatures.

Republic of Korea The Institute of Agricultural Engineering and Utilization, the Rural Guidance Bureau of the Office of Rural Development (ORD) and the College of Agriculture undertake research, development and extension. The Rural Guidance Bureau provides technical assistance and financial loans to farmers. However, there is no regular loan system and a 33-50 per cent governmental grant system has been discontinued. Most of the biogas development programme is being undertaken by the farmers themselves.

Rapid urbanization and the shortage of animal wastes slowed down the construction of family units in rural areas. The emphasis has shifted to the establishment of village-size units, gas storage and purification, and power generation. Many of the plants are not operated during the cold months, i.e. December- March, when temperatures drop as low as 17°C. Various attempts to maintain the temperature of the gas-holders through the provision of protective covers of straw or vinyl did not meet with much success. Provision of heating for the smaller plants was not justified. Conditions are more amenable in the southern part of the country which remains comparatively warmer during winter months.

ORD had helped install more than 30,000 small plants in the country by 1975. Farmers are not totally dependent on biogas for their energy needs. It supplies only 3-6 per cent of home heating, and less than half of the cooking needs. Each farming family has a cooking fire in addition to an unmodified LPG burner for biogas. The change of emphasis to large village-sized plants is intended to provide for most of the heating, cooking and power needs. Cow and pig excreta are the main feedstocks. ORD is engaged in the development of village-scale digesters. A 40-family, 155 m digester is operated at the Livestock Experiment Station, Suweon, established under the Korea-UK Farm Machinery Project. The plant utilizes 2.4 tonnes of dung obtained from the poultry farm and 170 cattle and has a retention time of about 40 days. Part of the gas is used to heat the digester to maintain the optimum temperature. Many more such units are being set up. Experiments are continuing on the use of biogas in kerosene engine applications and home heating. The Institute of Agricultural Engineering and Utilization is experimenting with PVC and concrete fixed-dome digesters. The College of Agriculture, Suweon, is working on a two-stage digester of reinforced plastic insulated with paddy husk. Use of night soil in biogas plants is also receiving attention. A plant using night soil as a feed-stock is operating in Kyong Jushi.

Lao People's Democratic Republic A number of demonstration units have been set up with the assistance of FAO, most of them of the Chinese fixed-dome design. A training course on biogas technology has also been organized.

Malaysia Biogas technology is new to Malaysia. Even though there are ample supplies of oil and natural gas, the Government has been giving attention to reducing dependence on conventional energy sources, especially on the part of small land-holders. One of the main hindrances to the propagation of biogas is the religious tradition which prohibits the handling of animal wastes, especially of pigs. Many biogas plants have been installed for reasons of sanitation rather than energy production. Some oil palm plantations digest the waste materials as treatment before disposal. However, the gas produced is not collected.

Research developments in biogas technology are coordinated by the National Institute of Scientific and Industrial Research.

Nepal Nepal is a landlocked mountainous country with an area of about 147,180 km^2 , of which 23.5% is plain,

60.5% rugged hills and 16% mountains. In 1984 Nepal had a population of about 16 mill. increasing annually by 2.6%.

Some 94% of the population is engaged in agriculture, 60% in the hilly areas, 40% in the Terai plain. Total forest area in 1977 was 4 mill. ha, plus 2 mill. ha scrubland, giving an annual yield of firewood of just under 7 millions m , while the estimated demand was just under 10 millions m , creating an annual deficit which is expected to rise to 8.6 millions m^3 /year by the end of the century (Krishna Yantra Bikash 1985). The livestock population is estimated to be about equal in numbers to the human population (H.M. Govt. 1985). It is estimated that the energy consumption in 1980/81 was 8,886 KT firewood, 210 XT agricultural wastes and 93 KT animal wastes (554 kg, 13 kg and 5.8 kg per capita/year, respectively). A rural household consumes about 55 l kerosene/year for lighting.

Organization of energy sector

Overall coordination is directed by the Water and Energy Commission (WEC), headed by its Secretary (WECS). This commission is responsible for planning in both energy and water. Biomass saving technologies, i.e. biogas plants and wood-saving stoves, have been give highest priorities. The Biogas and Agricultural Equipment Company (PV) Ltd. was established in 1977, with the joint investment of the Agricultural Development Bank (ADBN), the United Mission to Nepal and the Nepal Fuel corporation. ADBN is responsible for loans and subsidies to farmers, and acts as coordinator for activities.

Its annual budget is Rs. 11.258 (US' 536,100) with a break even point of 350 digesters constructed annually.

The potential for biogas plants fed by cattle manure (gobar), the only fuel at present available, is limited by the fact that only a very small percentage of farmers own 5 - 6 head of cattle, the minimum number required to operate the smallest digester. The Water and Energy Commission considers 375,000 family- sized units to be the upper limit for the market. Installations and Construction

Both fixed dome and floating drum plants are built, though the latter (at first the only model available) has been practically phased out in the last few years. Up to 1986, more than 2,060 digesters have been built, over 70% of them in the Terai. The figure of 200 - 300 constructed per year has remained fairly constant.

Between 1973 and 1979, plants of 7 and 13 m3 were built, while between 1979 - 1986 the dominant size was above 10 m (fixed dome). It was planned to raise the number of plants built per year to 1,120 by 1990. Characteristic of the Nepalese version of the fixed dome digester is that the dome is covered with earth to a depth of 60 cm, with the digestion chamber dug out underneath it in situ. Inlet and outlet chambers are built of brick. This digester is largely built of local materials. In the floating drum model, the taper design is preferred in the Terai, where the water table is high. The latter is the more productive model, with a specific yield of 0.42 and a retention time of 56.7 days (compared with 0.3 and 83 days for the fixed dome model) but this does not compensate for the higher specific cost of construction.

No solution has been found to the problem of low ambient temperatures: in winter, production decreases by up to 50% in the Terai, and ceases altogether in the hills.

Utilization of effluent

No detailed information is available on the use of the slurry: it is assumed that farmers spread it on their fields after drying.

Costs and benefits

Construction costs per m^3 decrease with increasing size of the digester, and are lower per m^3 for floating dome digesters. The Company is training masons, but its building capacity is still above demand. But for the subsidies, building and running the plants would not be economically feasible for the farmer. Only in the main towns, where firewood is expensive, and in the case of community digesters, whose yield replaces diesel oil to run machinery, does the cost:: benefit ratio balance. In the hills, the 25% subsidy compares with a 41% -subsidy that would be needed to bring the cost: benefit ratio to 1:1 or better. Clearly, the biogas digester is not, at this stage, an attractive proposition to small farmers.

Research and development

There is no overall coordination or planning in this field. The Biogas Company is conducting research on biomass digestion and biogas appliances (including the Red Mud Plastic cover), the Soil Science and Agricultural Chemistry Division at Trithuvan University in Katmandu conducts research on effluent utilization. United Mission to Nepal has tested a tunnel design, 20% cheaper that the fixed dome, but has not yet published results.

Experiences with biogas

The Biogas Company claims that 95% of the family-sized plants built are in operation, including most of the 709 floating dome models built in the earlier stages of the program, some of which are now 13 years old (1986) but this figure is unchecked and seems high. Of the 38 community digesters built, 80% are said to be in working order. Although the Government has given biogas technology the highest priority, it would be necessary to built a total of 375,000 digesters to achieve a saving of 12% in firewood. This would necessitate the training of more masons, while in the meantime demand is still below building capacity. A problem arises from the fact that farmers are not prepared to use effluent that has been produced with an admixture of night soil in the feedstock. The absence of comparative research on the production of different designs is a drawback.

Pakistan The Federal Ministry of Petroleum and Natural Resources, the Ministry of Natural Resources, and the Appropriate Technology Development Organization are engaged in biogas development. More than 100 plants of the floating gas-holder type had been set up by 1975. It was planned to set up 1,000 plants during 1981. The Government provides incentives to tile beneficiaries for the plants in the form of free appliances and gas-holders. The Ministry of Natural Resources has plans to create alternative energy sources in 50 selected villages mainly through the establishment of biogas plants. Some 35 biogas plants have been established by the Appropriate Technology Development Organization.

Attention is being given to the development and establishment of fixed-dome design plants because of their lower costs and the non-requirement for steel in their construction.

Papua New Guinea Work on integrated biogas systems, which include necessary provisions for the utilization of effluent for growing algae and aquatic plants, fish culture and fertilizer has been in progress since 1970. A bag-digester type of plant, much cheaper than the conventional design, is also being developed. The digester is made of 0.55 mm thick hypalon laminated with neoprene and reinforced with nylon sheet.

The Philippines Interest in biogas development grew with encouraging reports of the official mission of the Philippine Coconut Administration after its return from a European tour in 1965. In earlier days, the main interest in biogas stemmed from its pollution prevention and public health aspect" rather than from its fuel energy generation potential, as firewood was plentifully available. Now biogas is considered as the most feasible form of renewable energy resource for rural areas. A variety of feedstock consisting of domestic urban wastes, agricultural and animal wastes and food processing, distillery and industrial wastes are available for biogas generation.

Maya Farms has been the pioneer in the development of biogas technology since 1972. In order to obtain the necessary experience and to assess the suitability of different types of plants, demonstration models of Indian, Chinese and European types were set up. The models were later modified and used as pilot plants. A farm workers' dormitory night-soil biogas digester has also been designed. Biogas produced at the farm meets 40% of the total power requirement of the farm and is used for home applications, cooking vats in the canning plant, fueling of burners for heating and gasoline engines, running a feed mill, operating a 60-kVA electric generator and running farm vehicles. The organizations engaged in extension of biogas technology are the National Housing Authority, the Engineering Battalion of the Military, and the Department of Community Development. The Development Bank of the Philippines grants loans to farmers at low interest rates.

As a part of the development efforts, a "crash programme"" aimed at establishing plants in every region, province, town and locality, was initiated as early as 1976. More recently, the Bureau of Animal Industry (BAI) in cooperation with the Energy Development Board, launched the Biogas Barangay programme in 1980. Loans are made available to livestock owners through Financial institutions. Demonstration projects at the regional and provincial levels have been established by BAI. About 450 plants have been established under the programme. Fresh pig manure availability is estimated at 8.9 million metric tonnes per year, indicating a biogas production potential of 502 million m per year. The Indian design with a floating gas-holder is more popular. Recently, 10 digesters with a fixed-dome design have been established.

The National Institute of Science and Technology (NIST), University of Philippines, Central Luzon State University and Maya Farms are the institutions actively engaged in research. Various aspects, such as optimum requirements for biogas production, loading rates, feedstocks and their suitability, and microbiology are being investigated. Ten methanogenic isolates to be used as starter culture have been developed by NIST. Integrated biogas systems which involve cultivation of algae, fish and rice as components of the system are being developed at the University of Philippines.

Singapore There is not much scope for small-scale biogas plants in Singapore. Biogas produced at the sewage treatment works is used for operation of dual-fuel engines to generate electricity.

Sri Lanka Of the total energy consumed, 60% derived from firewood. Some 80% of the firewood is used in the rural areas. The forest reserves are being depleted and the availability of firewood is declining. Interest in various non-conventional energy sources, e.g. wind, biogas and waste materials, is developing. A demonstration plant was

established by the Industrial Development Board as early as 1974. Further research work is being carried out at the Peradeniya and Katubedda Universities. Biogas digesters are being established in a rural village under the Asian Rural Energy Project with the assistance of UNDP. An integrated farming system with biogas as a component is being developed at the In-service Training Institute at Gannoruwa.

__Thailand__ Thailand has a total population of some 50 million, growing at an annual rate of 2%, of which about 83% lives in rural areas. The country is divided into 5 regions: South, Central Plain, North, North-east and East, totalling 513,000 sq.km. About 75% of the population is engaged in agriculture, including pigs and cattle.

Four fifths of these farm families own less than 5 pigs or less than 4 cows. All but 10% of rural fuel is in the form of biomass (wood, charcoal, residues): in 1983 requirements were estimated at 41 million m . The total sustainable firewood supply was estimated at 28.5 million m in that year, according to one authority (Atal et al. 1984), but only 11 million m according to TSTR (1986). The rate of deforestation during 1976-80 was 333,000 ha per year, leading to a decline of 41% in the last 25 years.

Installations

The Central, North-east and South Regions have between them 94% of the plants built to date (1986). Central Region has 1,000 plants, almost equally divided into Type 1 floating drum models (in which the dome floats on the slurry) and fixed dome model=. Northeast Region has a total of 689, and South Region 689 plants, in both cases some 75% being fixed dome models (Source: Thailand Institute of Scientific and Technological Research).

The planned target of installations by 1986 was 10,000, but by the end of 1984, 5,000 had been built, at the most. 70% of these were built on cattle farms, 30% on pig farms.

The climate favours biogas production, except in the north, ambient temperatures enabling a potential specific yield of 0.3 to be attained, with a 20-30% decrease in winter. Use is almost exclusively for cooking, with a few adapted gasoline engines run on biogas. NEA is conducting research and disseminating small digesters to be used for lighting. More than half the families owning biogas plants use it in combination with other fuels.

Effluent utilization

Effluent is dried and spread on fields in a solid state, partially composted.

Costs and benefits

There is no subsidy on biogas digesters: the payback period on investment is in the region of 5 years or more, when biogas is used to replace charcoal. Consequently, the use of plants is confined to families with relatively high incomes. The Government does subsidize demonstration plants, paying 100% of their costs, and giving a subsidy of 50% for special promotion schemes: about 500 digesters have been built on this basis. In addition, training courses

and technical advice are free.

Experiences with biogas

Not more than 61% of the plants installed are operating properly. Of those abandoned, more than half worked for less than a year. Generally the reason is poor construction.

It is worthy of note that, unlike in India, Nepal, etc., farmers in Thailand are not familiar with the uses of dung, either as manure or as a fuel. In this respect, at least, the biogas program has proved a success, since nearly all plant owners use the effluent as fertilizer.

Organization of the biogas sector

The National Energy Administration (NEA) is the Government Agency responsible for the biogas program in all its administrative aspects, and chairs a national committee on biogas that includes representatives from all interested Ministries, Research Institutes and Extension Agencies. The NEA allocates subsidies for demonstration plants to various Extension Agencies, irrespective of design, cost or after-service. All Government Departments use their existing infrastructure for the dissemination of biogas plants; the most active is the Sanitation Department of the Ministry of Public Health, which provides construction and training through 7 regional centres. Its organizational structure for Regional Centre 4 is shown below, in Figure 13.6. The Department of Agriculture Extension maintains a network of provincial station, in which biogas is a minor activity, conducting courses and aiding farmers to build plants. The NEA has 7 regional energy development centres, dealing with biogas, but higher priority is given to tree planting and wood- savina stoves

[Fig. 13.4: Organizational structure of Regional Centre 4, Sanitation Division](#)

Viet Nam Tuhem Agricultural Station and the Institute for Electrical and New Energies, Hanoi, are involved in biogas research. Aspects like use of local construction materials, design of clay burners, and the use of different feedstocks and their mixtures are being investigated, A few demonstration units in different regions have been established. A national biogas development programme is being considered by the Government.

Latin America. **and the Caribbean** Very little information on biogas development is available for this region. The available information for various countries of the region is summarized below. The Organizacion Latinamericano de Energia encourages, coordinates and supervises biogas technology. It maintains close contact with member countries and keeps detailed records of research, development, construction and utilization. Altogether 8,712 plants have been built in the region, of which 72% are working adequately. Roughly one third are of the continuous type and one third semi-continuous. By and large, finance has come from outside donations or private sources. Consequently, little experience has been obtained at family level.

Argentina Although biogas technology has been in use for several decades, its use has been limited to decontamination of sewage, and until recently no use was made of the biogas. In addition, there are some plants being used for research. Therei. no central authority in charge of the topic. Since 1988, there are the beginnings of

efforts to disseminate the technology to rural areas and train workers. At that date, there were only 50 units in the country.

Barbados FAO funded the building of 4 units in the '80s, which were used for the treatment of sewage. Both biogas and effluent are being utilized.

Bolivia With the encouragement of OLADE (Organizacion Latinamericana de Energia) a small number of digesters have been built in the last 10 year, half of the in the rural sector. The predominant model is the OLADE-Guatemala (discontinuous) model (qv). Only some 30% of all the digesters are at present in operation (1988). Costs have been high. There is a technical problem concerning operation of biodigesters in the cold highland.

Brazil Development of biogas technology reached the pilot plant stage in 1979: widespread dissemination began the following year, under the aegis of the Ministries of Agriculture and Energy. A total of 7389 units, mostly of the Chinese type, had been built by 1988, of which 75% were working adequately at that date.

Auxiliary equipment has been successfully manufactured by private companies. The program has been well accepted in the rural sector, as well as in municipal sanitation, but the absence of subsidies and limited number of extension workers have limited dissemination. Although biogas is widely used for heating, lighting, cooking and the generation of electricity, the success of the program lies in the use of the effluent as fertilizer: it is in this field that return on investment" is found.

Colombia The few digesters that have been built have been installed by wealthy farmers. The dominant model (70%) is the Indian Floating Dome,

Costa Rica A small number of biogas digesters have been built by private investors and by the Institute of Technology. Although half-bag and full-bag models are preferred, building costs have been high. Consequently, rural development is very low. A National Biogas Commission operates under the Ministry of Energy and Mines.

Cuba The National Energy Commission and Ministry of Agriculture co-ordinate a National Biogas Group, under which some 550 digesters have been built since 1983, almost all of the small Indian type (6 m capacity). Financing has been done by Government. Most of the digesters serve remote rural dairies, where the gas generates their electricity. The percentage of digesters operating adequately is high.

Chile The few digesters that have been built are at the level of demonstration plants.

Dominican Republic The first demonstration plants were constructed by OLADE in cooperation with the National Energy Policy Commission in 1980.

Few plants have teen built (half of them the Chinese model) and of these, less than half are operating today.

Ecuador Biogas technology was introduced into the country by the Peace Corps and OLADE in 1974. The National Institute of Energy (INK) began a program for training and dissemination in 1980, and has been responsible for the building of half the 65 plants that existed in 1988. Most of these are of the Indian type. However, only 35% are operating adequately. The Government has subsidized the cost of a number of plants, in addition, others were built from donations by OLADE, the Peace Corps and FAO. Changes in methods of cattle management were necessary during the early stages, but in general, the technology has been well accepted in rural areas, though it is beyond the resources of small farmers.

El Salvador Technology has not advanced beyond research and a certain amount of training. Three quarters of the plants built are no longer working. The University, the Agricultural College and the Peace Corps are among the bodies involved in the introduction of biogas into the country.

Grenada A small number of units have been built since 1979, half of them by the Agricultural School, but no national program exists for training or dissemination. Plants are too costly for individual farmers, but the use of the effluent for fertilizer has been well accepted.

Guatemala Activities were initiated in the 50s by OPINA, a private firm. By 1977, 13 units had been built, all on the southern coast. Dissemination to rural areas began in 1980, and work was consolidated by the establishment of a National Biogas Group. 400 units had been built by 1988, a good percentage of which were in adequate operation at that date. The most widespread model is an adaptation of the semi-underground Sichuan model, built largely of local materials, developed by CEMAT, a non-government R & D centre.

Especially interesting is the success of dissemination to small farmers in highland areas. A number of private institutions are involved in construction, with training and overall coordination of programs for training and dissemination organized by the Government, which also endorses loans and credit, through the Institute of Agricultural Science and Technology.

Guyana OLADE and the National Energy Authority introduced the biodigester into the country in 1980. By 1988, 20 units had been built, mostly of the Chinese type, the most successful, others of the OLADE/Guatemala model. Little information is available on dissemination and training.

Haiti Only a very few demonstration plants had been built by 1988.

Honduras Over 100 plants have been built since OLADE and the Government introduced them into the country in 1980, the best accepted being the Chinese model, which represents 77% of the total. Funding was from external sources: OLADE, ACAITI and FAO.

Operation of plants that were totally subsidized has not proved successful, due to poor location, in some cases, or loss of interest in others. The cost of biogas units is outside the reach of poor farmers.

Jamaica With OLADE support, the Government, through the Ministry of Energy and the Scientific Research Council, began the dissemination of the technology in rural areas. FAO has also instituted training and promotion schemes. 41 units had been built by the end of 1988, 71% of them being the Chinese model. There is a loan system for their construction, and returns have been good, especially in the use of effluent as fertilizer.

Mexico A few demonstration models have been built, but the level of operation is low. Since energy sources are cheap in Mexico, interest in biogas is correspondingly low.

Nicaragua Few units have been built; and many of these were of the piston-flow horizontal type, with which experience has not been good.

Panama The technology program began in 1979, but only demonstration models have been built, mostly the horizontal type with piston flow. A community digester project was unsuccessful.

Peru 61 digesters have been built since 1979, 77% of the Chinese model. Three quarters were working adequately up to 1988. Costs have been notably lower than in neighbouring countries.

Trinidad and Tobago The Government of Trinidad and the University of West Indies (Chemical Engineering Department) are conducting biogas research. Efforts are being made to develop a suitable anaerobic digester for sugarcane bagasse.

Uruguay Six out of 9 demonstration plants built in the 80s are of the Indian type. Efforts are now being made to introduce the Chinese model into small dairy cooperatives.

Venezuela Given the availability of oil, few plants have been built, and those for demonstration purposes. They are used for sewage treatment and the generation of electricity. Initiative came from The Ministry of Energy and Mines and the School of Agronomy of the University. No national program exists; but the use of firewood as fuel in rural areas constitutes a problem.

Africa

Burundi Biogas technology was introduced in 1981, since which time 140 plants have been built, mostly family units of the Chinese or BORDA type.

Kenya In the 70s, a national program, the Special Energy Program, began the dissemination of biogas plants, aiming at medium-sized farms. In the first decade, a wide diversity of types were built, most of which proved either unsuited to local conditions or defective in construction. Learning from this experience, by 188 some 250 plants had been built, backed by a training program, supervision of construction quality, and concentrating on a single type (BORDA floating cover). There is no subsidy available to users.

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Appendix 2: Glossary

Acid-forming Bacteria - The group of bacteria in a digester that produce volatile acids as one of the by-products of their metabolism.

Aerobic - In the presence of free oxygen.

Aerobic Bacteria - Bacteria which live and reproduce only in an environment containing oxygen which is available for their respiration, such as atmospheric oxygen or oxygen dissolved in water.

Alkaline - The condition in which there is present a sufficient amount of alkali substances to result in a pH above 7.0.

Anaerobic - Without the presence of free oxygen.

Anaerobic Bacteria - Bacteria that live and reproduce in an environment containing no free or dissolved oxygen.

Anaerobic Contact Process - An anaerobic digestion process in which the microorganisms are separated from the effluent slurry by sedimentation or other means and returned to the digester to increase the rate of stabilization.

Anaerobic Digester - A reactor which is constructed to degrade organic matter by anaerobic bacteria.

Anaerobic Digestion - The process of degradation and stabilization of organic materials by the action of anaerobic bacteria with the production of biogas (biomethanation). The process is very slightly exothermic (heat- producing).

Active Volume - The actual volume available in a digester for bacterial action. It is calculated by subtracting the volume occupied by grit and scum from the volume of the digester occupied by sludge.

Batch-Feed Digester - A digester which retains all the feedstock added in a single charge. Discharge of the entire batch occurs at the end of the retention time.

Benefits - Tangible benefits of a biogas system are those that are easily quantifiable and have a monetary value. Such benefits include the value of the gas and the digested "furry produced, both as fertilizer and

as peat-moss substitute. Intangible benefits are those that are not so easily quantified or related to a monetary value. Examples include the value of an improvement in environmental sanitation, odour prevention et Biofeed - Solids recovered from digested sludge and used as animal fodder.

Biogas - A mixture of gases, predominantly methane and carbon dioxide, produced by anaerobic digestion. Traces of hydrogen sulphide and ammonia are present in varying quantities.

Biogas Plant - A plant used to process organic matter to produce biogas and sludge.

Buffer Capacity - A measure of the resistance to changes in pH caused by the compounds in the sludge.

Cabutz - The solid fraction that remains after the separation of the digested slurry from the thermophilic anaerobic digestion of cow manure.

Carbon dioxide - CO_2, The gas resulting from burning or complete oxidizing of any carbon source.

Carbon monoxide - CO, The gas resulting from incomplete burning or incomplete oxidizing of any carbon source.

Calorific Value - The amount of heat that can be obtained from a fuel, usually expressed in terms of calories per unit weight (or volume) of the fuel.

Catabolism - Destructive metabolism involving the production of energy and resulting in the breakdown of complex materials within the organism.

Carbon/Nitrogen Ratio (C/N Ratio) - The ratio of organic carbon to that of total nitrogen.

Coliform - A rod-shaped bacterium found in intestinal tracts of most animals, which is often used as an indicator to detect faecal contamination.

Composting - Controlled decomposition of organic matter under aerobic conditions by which material is transformed to humic material. The process is exothermic resulting in a rise in temperature. The process is used to improve the quality of manure as organic fertilizer.

Continuous-Feed Digester - A digester which is regularly charged continuously or with small amounts of fresh slurry at short intervals; the freshly charged slurry automatically displaces an equal volume of effluent and the process continues without interruption.

Degradation - The breakdown of (organic) substances by chemical, physical, and/or biological action.

Denitrification - Anaerobic reduction of nitrogen compounds, such as nitrates, to elemental nitrogen.

Detention Time - The theoretical period of residence in a given volume or unit. It is normally calculated by dividing the active volume of the unit by the rate of flow of the liquid through it.

Dewatering - The process of removing water from the effluent slurry of a digester by evaporation or filtration.

Digester - The vessel in which anaerobic digestion takes place, which may be constructed also to store the biogas produced by anaerobic digestion.

Digester Slurry - Mixture of fermented organic matter and water.

Digestion - The controlled decomposition of organic substances, normally under anaerobic conditions.

Effluent - The sludge or spent slurry emerging from a digester.

Endothermic reaction - The chemical reaction in which energy is needed (or absorbed from the surrounding) in order for it to take place.

Exothermic reaction - The chemical reaction in which energy is liberated to the surrounding) when it takes place.

Enzyme - A complex organic substance (mostly a protein) produced by living cells and having the property of accelerating transformations such as digestion processes.

Facultative - The ability of microorganisms to live under either aerobic or anaerobic conditions.

Floating Gasholder - A biogas container consisting of an inverted open top tank floating over a liquid such as digester slurry or water; it rises when it fills with biogas and sinks as the gas is depleted. The weight of the floating cover controls the pressure of the gas which is discharged from the gasholder.

Gasholder - A separate system that receives and stores the gas produced in a digester.

Grit - Heavy mineral matter such as sand, gravel, and cinders, often present in digester feedstock which accumulates in the bottom of the digester.

Humus - The end product of a comporting process consisting mainly of humic acids, lignin and cellulose.

Hydraulic Retention Time - The average time that a liquid stays in a reactor before it is discharged. It is equal to the active volume of the reactor divided by the flow rate of the liquid entering it. It is usually expressed in days but may be as short as hours.

Inactivation - The process by which parasite eggs, wild fungi, pathogenic bacteria and viruses are rendered inactive and hence unable to propagate.

Influent - The feeding materials or slurry incoming to a digester.

Inoculant, Inoculum - Any material, such as digested feedstock, that is added to a newly started digester to start the degradation of organic matter and the production of methane.

Inorganic Matter - Material in solution or suspension, such as sand, salt, iron, calcium, and other minerals, which are not degraded by microorganisms.

Manure - Animal excrete, normally faecal matter from livestock.

Manure Slurry - The mixture of manure and water coming from livestock pens.

Mesophyllic - Within a moderate temperature range, normally 30-40°C.

Metabolism - The biochemical changes in living cells by which energy is provided for vital processes and activities, and new material is synthesized (catabolism + anabolism).

Methane (CH_4) - A colourless, odourless, flammable gas and the main constituent of natural gas, coal gas and biogas.

Methane Forming Bacteria - The group of bacteria in a digester that uses acetate and H_2 as energy sources and produces methane.

Night Soil - Human faeces and urine collected by buckets or vacuum trucks.

Organic Matter - Materials which come from animal or vegetable sources. Organic matter generally can be degraded by microorganisms.

Pathogen - Disease-causing organism.

Peatrum - The sieved digested slurry after thermophilic digestion of cattle rumen content and manure.

Plug Flow - Movement without mixing in the axial (longitudinal) direction in a digester. The opposite of complete-mixing in digesters.

Retention Time - The number of days that organic matter or bacteria remain in the digester. See also detention time.

Sludge - The slurry of settled particles resulting from the process of sedimentation.

Sludge Digestion - A process by which organic matter in sludge is gasified, liquefied, mineralized, or converted to a more stable form, usually by anaerobic organisms.

Specific gas volume - Daily volume of biogas produced per unit volume of digester.

Supernatant - Liquid removed from settled sludge. Supernatant commonly refers to the liquid between the sludge in the lower portion and the scum on the surface of an anaerobic digester or the liquid material left after separation of the slurry.

Suspended Solids - Solids that are in suspension in water or other liquids.

Thermophilic - Digestion at a relatively high temperature, normally in the range of 50-70°C.

Toxicity - A condition that will inhibit or destroy the growth or function of a living organism.

Total Solids - The sum of dissolved and suspended constituents in a sample, usually stated in milligrams per litre or percent.

Volatile Acids - Short chain (C_1 - C_2) fatty acids which are produced by acid forming bacteria. They are soluble in water, can be steamdistilled at atmospheric pressure, and are commonly reported as equivalent acetic acydlatile Solids - The solids that volatilize and therefore are lost on ignition of a sample of dry solids at 55°C - Representing the organic matter in the sample. The volatile solids are expressed as a percentage of the total solids.

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Appendix 3: Institutes and research workers

Contents -

BELGIUM

1. Willy Verstraete; State University Gent; Lab. Microbial Ecology; Coupure L 653; 9000 Gent.

BRAZIL

1. IPT: Instituto de Pesquisas Technologicas do Estado de Sao Paolo S/A (Institute of Technological Research of the State of Sao Paolo).

2. CETESB: Companhia de Technologica de Saneamento Ambiental (Environmental Sanitation Technology Company, State of Sao Paolo)

3. USP-Sao Carlos: Universidade de Sao Paolo. Campus of Sao Carlos University of Sao Paolo).

4. Instituto de Saneamento Ambiental da Pontificia Universidade Catolica do Parana (Environmental Sanitation Institute of Catholic University, State of Panama)

5. Companhia de Saneamento Basico do Estado de Sao Paolo (Water and Sewage Company of the State of Sao Paulo)

6. Universidade Estadual Julio Mesquite Filho (State University Julio Mesquite Filho State of Sao Paulo)

7. Empresa Brasileira de Assestencia Technicae Extensao Rural (Brasilian Company for Technical Assistance and Rural Extension)

8. Empresa Brasileira de Pesquisa Agropecuaria (Brasilian Company for Agricultural and Feedstock Growing Research).

9. Companhia Energetica de Sao Paulo (Energy Company of the Stat of Sao Paulo)

10. Universidade Federal de Pelotas (Federal University of Pelotas, State of Rio Grande do Sul).

11. Companhia de Saneamento do Parana (Water and Sewage Company of the State of Parana).

12. Fundacao de Amparo a Technologica e Meio Ambiente (Foundation for Technology and Environment, State of Santa Catarina)

13. Coordenacao de Programas de Pos-Graduacso em Engenharia da Universidade Federal do Rio de Janeiro (Coordination of Post-graduation Programmes in Engineering, Federal University of Rio de Janeiro).

14. Superintendencia dos Recurses Hidricos e Meio Ambiente (Superintendence of the Water Resources and Environment, State of Parana).

15. Paulo Nobre; SABESP; Rua Costa Carallio 300; 05459 Sao Paulo SP

16. Sonia Vieira; CETESB; Av. Prof. F. Hermann Jr., 345; 05459 Sao Paulo SP

CANADA

1. University of Manitoba.

2. The Canada Centre for Inland Waters at Burlington, Ontario

3. The Engineering and Statistical Research Centre

4. The National Research Council.

5. Department of Bioresource Engineering University of British Columbia.

6. IDRC - International Development Research Centre, Box 8500, Ottawa.

7. University of Western Ontario

8. Laval University.

9. University of Saskatchewan.

10. Department of Microbiology, University of Guelph.

11. Department of Civil Engineering, University of Nova Scotia.

12. Renewable Energy Division, Energy Mines Resources, Canada.
13. University of Ottawa.

CHINA

1. Chengdu Biogas Research Institute, Agriculture (China Chengdu Biogas Research and Training Centre fro Asia and the Pacific).

2. Sichuan Provincial Rural Energy Office, Chengdu/Sichuan.

3. Chengdu Biology Institute of the Chinese Academy of Sciences.

4. Sichuan Provincial Institute for Environmental Protection, Chengdu/Sichuan.

5. Biology Department of the South Western Teacher's University Chongking.

6. Wuhan Energy Research Institute, Wuhan.

7. Department of Environmental Engineering, Chengdu University of Science and Technology, Chengdu/Sichuan.

8. Jiangsu Provincial Biogas Research Institute.

9. Zhejiang Provincial Solar Energy and Biogas Research Institute, Hangzhou.

10. Zhejiang Agricultural University, hangzhou.

11. Shanghai Industrial Microbiology Institute, Shanghai.

12. Beijing Municipal Institute for Environmental Protection, Beijing.

13. Department of Environmental Engineering, Quinhua University, Beijing.

14. Beijing Microbiology Research Institute, Beijing.

15. Guangzhou Energy Research Institute of the Chinese Academy of Sciences, Guangzhou.

COLUMBIA

1. Alvaro Orozco; Universidad de Los Andes; Depto de Ingenieria Civil; Universidad de Los Andes; Apartado Aerco 4976; Bogota.

DENMARK

1. The Coordination Committee for Cooperative Biogas Agency; Landemarket 11, DK 1119, Dams Energy A, Copenhagen K.

2. STUB (urn coordination group for technical development of biogas) & The Biogas Laboratory Secretariat: Technological Institute, Gregersensvei DK 2630 Taestrup.

3. The Test Station for Biomass SJF, Bygholm, DK 8700 Horsens.

4. The National Agricultural Test Station, Askov.

5. Hojbogaard Biogas Plants Ltd., DK 5580 Norre Aaby.

6. Institute of Thallophytes, University of Copenhagen.

7. University of Aalborg.

8. Dept. of Vet. Microbiology, Royal Veterinary and Agricultural University, Copenhagen.

9. Dept. of Crop, Husbandry and Plant Breeding, Royal Veterinary and Agricultural University, Copenhagen.

10. Institute of Agricultural Economics, Copenhagen.

11. Danish Meat Products Laboratory, Ministry of Agriculture, Copenhagen.

EGYPT

1. The American University, Cairo.

2. Faculty of Agriculture, Cairo University, Cairo.

3. National Research Centre, Dokki, Cairo.

4. Soils and Water Research Institute, Agricultural Research Centre, Giza.

5. Egyptian Solar Energy Society, Cairo.

6. Renewable Energy Supreme Council, Ministry of Electricity and Energy, Cairo.

7. IDRC - CP 14 Orman, Giza, Cairo.

ECUADOR

1. Olade - Organizazacion Latinoamericana de Energia, P.O. Box 6413 C.C.I., Quito.

FINLAND

1. Microbiology Institute, University of Helsinki, Helsinki.

2. Biotechnology Laboratory, Technical Research Centre, SF 02130 Espoo.

3. Energy Laboratory University of Oulu, Oulu.

4. University of Joansuu, Joenssu.

5. Agricultural Centre of Mikkeli.

6. Tampere Univ. Technology/Water Supp. & Sanitation, Tampere.

7. Finnish Pulp and Paper Research Institute, Helsinki

FRANCE

1. National Institute of Agronomic Research (INRA).

2. National Institute of Applied Sciences (INSA).

3. Institute of Applied Chemical Research (IRCHA).

4. National Centre of Scientific Research (CNRS).

GERMANY

1. Federal Research Institute for Agriculture, Institute for Technology (FAL), D 3301 Braunschweig-Volkenrode.

2. Tansfer Centre Biotechnology, Hochschule Bremerhaven, An der Karlstadt 8, D 2850 Bremerhaven.

3. University Hannover, D 3000 Hannover.

4. University Hohenheim, D 7000 Stuttgart 70.

5. University Kiel, D 2300 Kiel.

6. University Muenchen, D 8000 Muenchen.

7. University Oldenburg, D 2900 Oldenburg

8. Institute for Agricultural Technology, Voettinger Str. 36, D 8050 Friesing-Weihenstephan.

9. Bremen Overseas Research Development Association, Bahnhofsplatz 12 (Uebersee-Museum), D 2800 Bremen.

10. Society for Technical Cooperation (GTZ) D 6236 Eschborn/Ts.

INDIA

1. Gobar Gas Research and Training Centre, Etawah.

2. Central Food Technological Research Institute, Mysore 570013.

3. Orissa Renewable Energy Development Agency, Bhubaneswar.

4. ESCAP Regional Centre for Technology Transfer, Bangalore.

5. Centre of Science for Villages, Wardha.

6. Resources Development Institute, Bhopal.

7. Khadi and Village Industries Commission, Bombay.

8. Panjal University, Chandigarh.

9. Indian Institute of Technology, New Delhi.

10. National Environment Engineering Research Institute, Nagpur.

11. Centre for Application of Science and Technology to the Rural Areas (Astra), Indian Institute of Science, Bangalore.

12. Department of Non-conventional Energy Sources, Ministry of Energy, New Delhi.

13. Indian Agricultural Institute, New Delhi.

14. National Institute of Waste Recycling Technology, Bombay.

15. IDRC - 11 Jor Bagh, New Delhi 110 003.

IRAN

1. Biogas Department of the Ministry of Energy, Teheran.

2. Solar Energy Centre of the Engineering School, Shiraz University.

ISRAEL

1. MIGAL - Galilee technological Centre, Kiryat-Shmona 10-200.

2. Department of Environmental and Water Resources Engineering, Technion, Israeli Institute of Technology, Haifa 32000.

3. The Hebrew University, Jerusalem.

4. Centre for Biotechnology, University of Tel-Aviv, Ramat Aviv, Tel-Aviv.

5. Israeli Institute for Biological Research, Rehovot.

ITALY

1. Andrea Tilche; ENEA; Fare Dept.; Via Mazzini 2, 40138 Bologna.

2. Fabrizio de Poli; Environmental Engineering Dpt.; CRE Cascciaa; Via Angillarese; 0060 Roma.

3. Alberto Rozzi; Instituto di Ingegneria Sanitaria, Politecnico di Roma.

JAPAN

1. Bioindustry Development Centre (BIDEC) Dowa Building 10-5 Shimbashi 5-chome, Minate-ku, Tokyo 105.

2. Fermentation Research Institute, Agency of Industrial Science and Technology, Ministry of International Trade and Industry 1-3, Higashi-lchome, Tsukuba City, Ibaraki Prefecture 305.

3. New Energy Development Organization (NEDO) Sunshine 60 bldg., 1-1 Higashi Ikebukuro 3-chrome, Toshima-ku Tokyo 170.

4. Kurita Water Ltd., Moto Yoda Kurita; 7-1 Wakamiya; Morinosato; Atsugi City 243-01.

5. Tsugio Kono; Aqua Renais. Res. Asso.; Toranomon Takagi Building 1-7-2 Nisisinbasi, Minato-ku, Tokyo 105.

REPUBLIC OF KOREA

1. Ajou University Kyunggi Do.

2. Institute of Agricultural Science, Suwoon.

3. Korean Advanced Institute of Science and Technology, Seoul.

4. Seoul National University, Sweon.

5. Ministry of Energy and Resources, Seoul.

NEPAL

1. Swiss Association for Technical Assistance, Kathmandu.

2. Institute of Engineering, Kathmandu.

3. Institute of Science and Technology, Tribhuvdn University, Kathmandu.

4. Development and Consulting Services, Butwal.

5. International Centre for Integrated Mountain Development, Kathmandu.

6. Research Centre for Applied Science and Technology, Kathmandu.

7. Agricultural Development Bank, Kathmandu.

8. Gobar Gas Co., Lalitpur.

9. Gobar Gas Company, Kathmandu.

10. United Mission to Nepal, Kathmandu.

THE NETHERLANDS

1. Agricultural University of Wageningen (LUW), Wageningen.

2. Catholic University of Nijmegen (KUN), Nijmegen.

3. technical University of Delft (TUD), Delft.

4. University of Amsterdam (UVA), Amsterdam.

5. Institute for Storage and Processing of Agricultural Products (IBVL), Wageningen.

6. Central Institute for Nutrition Research.

7. Institute of Applied Natural Sciences (TNO/MT).

8. Netherlands Institute of Agricultural Engineering (IMAG).

9. Aris Schellinkhout; DHV Consulting Engineers; PO Box 85, 3800 Am Amersfoort.

10. Louse Wildschut; Haskoning BV, 6500 AD Nijmegen.

11. International Institute for Hydraulic and Environmental Engineering, PO Box 3015, 2601 DA Delf.

NEW ZEALAND

1. Centre for Waste Treatment and Biogas Technology, Invermany Agriculture Centre, Ministry of Agriculture and Fisheries, Mosgiel.

2. Biotechnology Section Forest Research Institute, Rotoura.

3. Biotechnology Department, Massey University, Palmerston.

4. University of Canterbury, Christchurch.

SPAIN

1. Instituto de Energies Renovables, CIEMAT, Ciudad Universitaria, Madrid.

2. Escuela T.S. Ingenieros Agronomos, Departemento de Ingenieria Rural, Ciudad Universitaria, 28040 Madrid.

3. Instituto par la Diversification y Ahorro Energetico IDAE, Paseo de la Castellana 95, Madrid.

4. Empresa Nacional Adaro SA ENADIMBA, Doctor Esquerdo 138, Madrid.

5. Instituto de las Grasa, CSIC, Seville.

6. Diputacio de Barcelona, Seccio Technica d'Agricultura Urgell 187, Barcelona.

7. Universitat Autonoma de Barcelona, Department de Quimica Technica Bellaterra, Barcelona.

8. Universidad de la Laguna, Departemento de Quimica Technica, La Laguna, Tenerife.

9. Universidad de Santiago de Comostela, Departemento de Ingenieria Quimica, Avenida de las Ciencias B/N, Santiago de Compostela.

10. Fernando Polanco; Depart. de Ingenieria Quimica; Facultad de Ciencias; Universidad de Valladolid; 47011 Valladolid.

SWEDEN

1. Technical Microbiology and Chemistry Centre, Lund University, Lund.

2. Swedish Institute of Agricultural Engineering, Uppsala.

The Royal Institute of Technology, Stockholm.
Swedish Water and Air Pollution Research Institute, Stockholm.

THAILAND

1. Asian Institute of Technology, PO Box 2754, Bangkok 10501.

2. Chiang Mai University, Faculty of Engineering, Chiang Mail

3. Mahidol University, Bangkok 10400.

4. Kasetsart University, Bangkok 10900.

5. Chuldlongkorn University, Bangkok 10500.

6. Maejo Institute of Agriculture Technology, Sansai, Chiang Mai 50290.

THE UNITED STATES OF AMERICA

1. Gas Research Institute, Chicago.

2. Agricultural Engineering Department, Cornell University, New York.

3. University of Illinois.

4. Solar Energy Research Institute, Golden, Colorado.

5. University of Utah, Salt Lake City.

6. National Academy of Sciences, Washington, D.C.

7. Centre for Energy and Environmental Studies, Princeton University, N.J.

8. Joseph Visalli; N.Y. State Energy Research and Development Authority; 2 Rockefeller Plaza; Albany, N.Y. 12223.

S.M. Switzenbaum; Environmental Engineering Programme, Department of Civil Engineering, University of Massachusetts, Amherst.
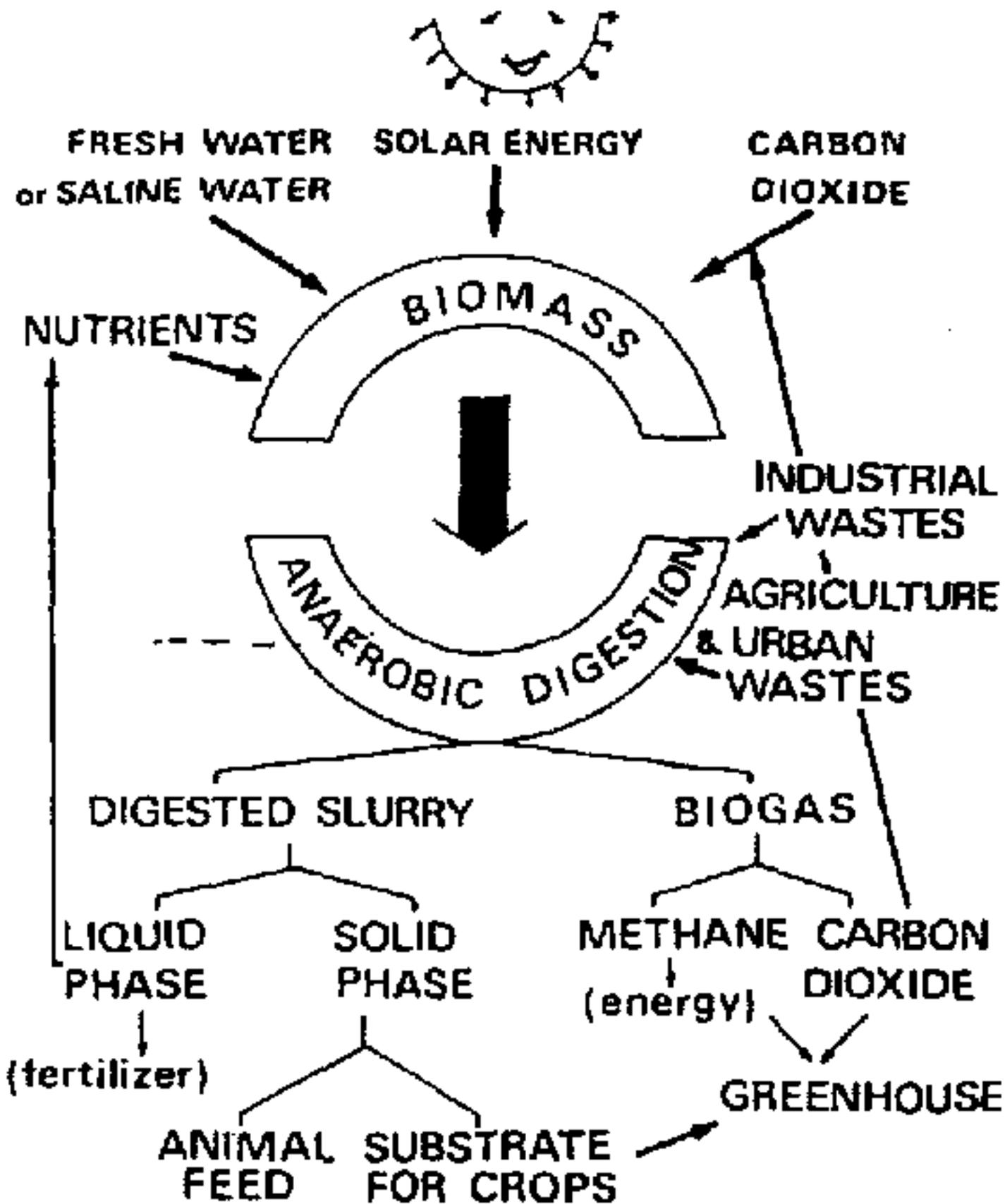
Biogas processes for sustainable development

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[Appendix 3: Institutes and research workers](#)

http://www.fao.org/docrep/T0541E/T0541E01.GIF

CONVENTIONAL DIGESTER

HIGH — RATE DIGESTER
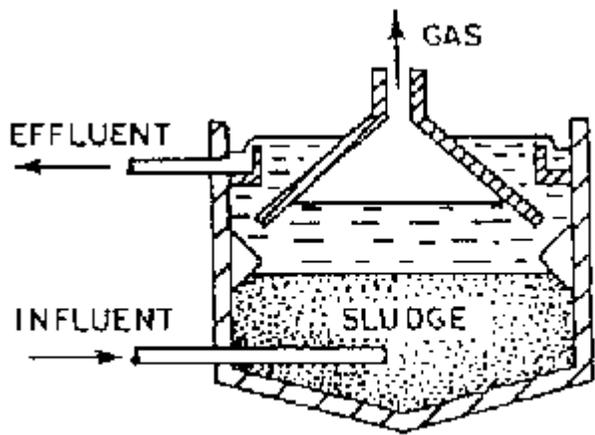
UPFLOW ANAEROBIC SLUDGE BLANKET
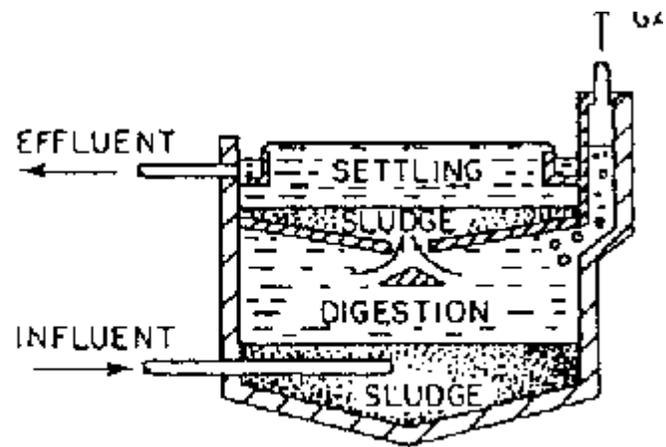
ANAEROBIC CLARIGESTER

ANAEROBIC CONTACT PROCESS

SCUM

SUPERNATANT LIQUID

SLUDGE

CONVENTIONAL DIGESTER

MIXING
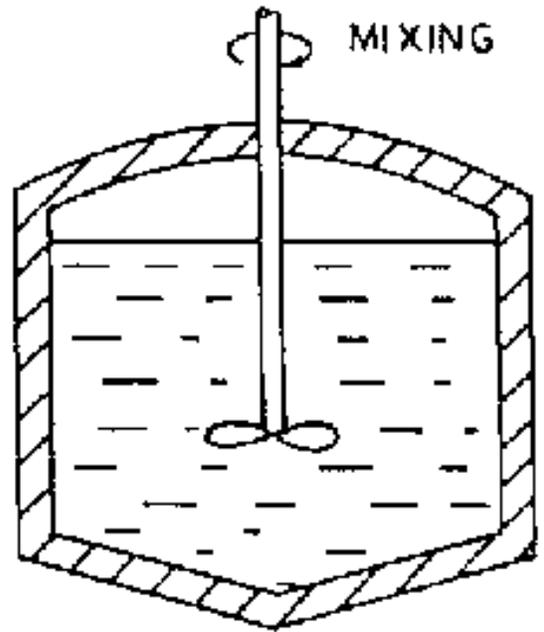
HIGH — RATE DIGESTER
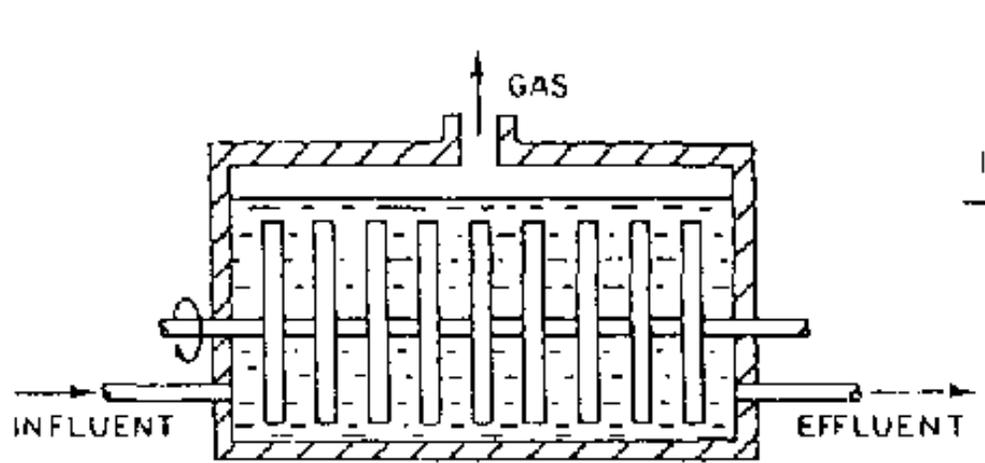
ANAEROBIC ROTATING BIOLOGICAL REACTOR

ANAEROBIC BAFFLED REACTOR

Protein

Carbohydrate

Lipid

Cellulose
Starch
Pentosan (Hemicellulose)
Pectin

Amino acids

Methanol

Sugars

Glycerol

Fatty acids

NH_3

Formate
CO_2
H_2

Acetate

Ethanol
Lactate
Succinate
Propionate
Butyrate

CH_4

$$CH_3OH$$

$$CH_3COOH \ (2.0)$$

$$X_1 \ CH_3 \quad \xrightleftharpoons[]{(0.85)} \quad X_2 \ CH_3 \xrightarrow{(0.85)} \ \xrightarrow{(1.0)} CH_4 \ (1.0)$$

$$(1.0)$$

$$(0.15)$$

$$Y - \overset{\overset{\textstyle O}{\|}}{C} - OH$$

$$(1.0)$$

$$[1.15] \qquad (0.15) \qquad (1.0)$$

$$CO_2 \ (1.0)$$

EUKARYOTES   EUBACTERIA   ARCHAEBACTERIA

EUKARYOTES   ANCESTRAL EUBACTERIA   ANCESTRAL ARCHAEBACTERIA

UNIVERSAL ANCESTOR
(PROGENOTE)

REMOVABLE COVER

GAS OUTLET

FERMENTING
SLURRY

REACTOR

COVER FOR SOLIDS REMOVAL

LIQUID OUTLET

INLET

GAS OUTLET ←

REMOVABLE MANHOLE
COVER SEALED WITH CLAY

LOOSE COVER

GAS

1000 mm
max

SLURRY

DISPLACEMENT TANK

OUTLET PIPE

GAS OUTLET

GAS HOLDER

CENTRAL GUIDE

MIXING PIT

OUTLET PIT

INLET PIPE

SLURRY

PARTITION WALL

GAS PIPE

GAS

d

SLURRY

LEVELLED
SURFACE

150mm aprox

INLET

OUTLET

LAYER OF
ABOUT 70mm OF
COMPACTED BACKFILL

INLET PIT

FLEXIBLE MEMBRANE

GAS OUTLET

OUTLET PIT

GAS

SLURRY

COMPACTED BACKFILL AND INSULATION

SECTION

GAS OUTLET

GAS

LIQUID OUTLET

PACKING

REACTOR

LIQUID INLET

PACKING SUPPORT

GAS OUTLET

GAS SPACE

LIQUID
INLET

LIQUID OUTLET

LIQUID

SLUDGE
BLANKET

COMPOSTING TIME (months)

ASH   ORGANIC MATTER

PRODUCTION PER YEAR

6.650 Tons of dry matter processed

	BIOGAS		SLURRY	
	1,014,000 m^3		1,196 Tons, 8.9% solids	
	ELECTRICITY	HOT-WATER	LIQUID	PEATRUM
	546,000 Kwh	167.7 T fuel	+1:1 H_2O	25% solids
				3,900 m^3
			1,108 Tons	416 Tons
Prices/unit($):	0.07	0.375	-	50-65
Total yearly income($):	38,220	62,887	-	195,000-253,500
TOTAL YEARLY INCOME ($)				296,100-354,600

VARIABLES

1. STABLE
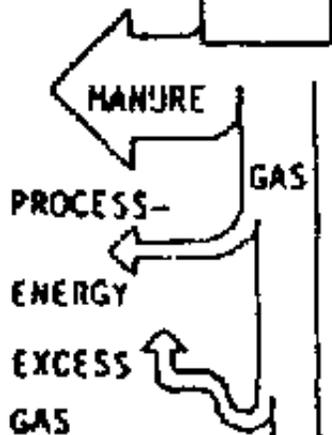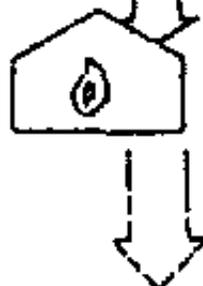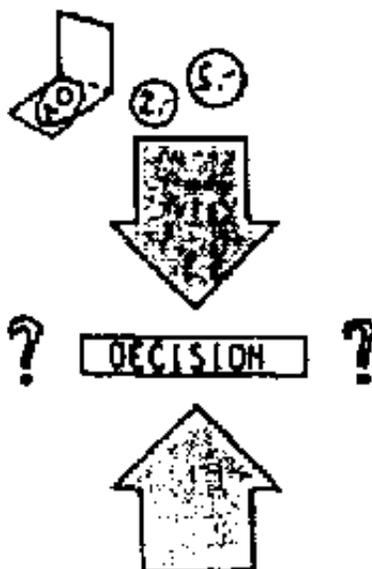
- Type of animal
- Number of animals
- Manure removal
- Dilution

2. PROCESS PARAMETERS

BIO

MANURE

GAS

PROCESS-

- Fermentation tempe-
  rature
- HRT
- Loading rate

3. DESIGN CRITERIA

ENERGY

EXCESS

GAS

- Fermenter design
- Insulation
- Heating system
- Mixing system

4. GAS UTILIZATION

- Gas utilization
- Gas storage
- Gas upgrading

5. PROFIT

? DECISION ?

- Cost of comparable
  energy source
- Future price develop-
  ment
- Other effects
  (odour reduction,
     hygiene, etc.)
- Amortization

– Amortization

6. RUNNING COSTS

– Cost of operation

(after Kaufmann , 1984)

```
                    ┌─────────────────┐
                    │ Liaoning        │
                    │ Provincial STC  │
                    │ in Shenyang     │
                    └─────────────────┘
                             │
┌──────────────┐    ┌─────────────┐    ┌──────────────────────────┐
│ Center for   │◄──►│   LPRIER    │◄──►│ China Development Center │
│ New Energies │    └─────────────┘    │ of RMP's for BGT, Yinkow │
└──────────────┘           │           └──────────────────────────┘
                           │                        │
                    ┌─────────────┐         ┌──────────────┐
                    │     R&D     │         │ Northern     │
                    └─────────────┘         │ Company      │
                           │                └──────────────┘
                    ┌──────────────────┐
                    │ 1 Director       │
                    │ 2 Vice Directors │
                    └──────────────────┘
```

- Test Workshop
- Information
- Planning and Administration
- 1 Station 70 km from Yinkow
- Laboratories
  - Solar
  - Biogas
  - Materials for New Energies
  - Utilization of Thermal Energies
  - Computer

```
                                          Sanitation Centre
      ----------------------------------  16 Sanitation Trainees
      |                                    (10 for 10 Provinces)
      |
      |                                       10 Provinces
      |                                    10 Sanitation Centres
      |                                 (2) 3-4 Sanitation Trainers ea.
Training courses
in all aspects of                       126 District Health Officers
sanitation, 10 days                     2-3 Public Health Offices ea.
including biogas
40 SVC per course                       1,000 Tambon Health Stations
      |                                    1 Station per Tambon
      |                                    1 Sanitation Health Worker ea.
      |
      |
      |
      |                                    10 Villages per Tambon
      -------------------------------- 1 Sanitary Village Craftsman
                                           (SVC) per Village
```