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Biogas production from agricultural wastes

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'Biogas' is the word used to denote the mixtures of methane and carbon dioxide produced by bacterial action, in vitro, on various organic substrates. 'In vitro', because similar mixtures of methane and carbon dioxide are formed by essentially the same bacterial actions in the gut of animals (in particular the rumen and similar organs of the herbivore gut; see previous papers) and in decaying vegetation in marshes and river beds.

In most of the natural systems formation of methane is undesirable, and if the reactions can be controlled, say in ruminant feeding, control is in the direction of reduction of methane production. On the in vitro man-made systems, production of methane is the objective and control is, for 2 reasons, in the direction of increasing this. Production of biogas from wastes in a structurally-defined system (the 'anaerobic digester') is not a new technology: a controlled anaerobic digestion has been used for 60 years or so in the treatment of municipal sewage sludges for the reduction of pollution and nuisance caused by these sludges. An index of the extent of pollutant reduction is the amount of biogas produced, so, obviously, maximizing gas production maximizes pollution control. However, in many sewage works the biogas is used as a fuel for powering the aerobic side of the sewage treatment and for lighting, heating, etc., in the works, as a substitute for mains electricity, gas or oil fuels. So maximum gas production is again desirable.

Since biogas production on a large scale has been going on for so many years, one might reasonably ask why an energy system based on biogas is not now widespread? There are 2 or 3 main reasons. While gas production in a big sewage works is large, it is only obtained by collecting and processing the excreta from many thousands, or millions, of people. This involves miles of sewers with large tanks and other plant at the sewage works. All this is expensive and the construction and costing was not based on producing fuel gas at a price competitive with low-cost oil and coal-based fuels, but on doing the pollution control needed for the healthy living of a city population; the biogas fuel helped to cut running costs. Secondly coal and coal-gas, and particularly oil, were in plentiful supply. While it was known that other waste organic matter could be used to produce biogas, the topic was not, generally, pursued. Biogas production from agricultural wastes was attempted in times of crisis, for instance war time, to obtain a substitute for scarce petrol for vehicles, but with the coming of peace the plants were largely forgotten about. They were forgotten because the plants had running problems, they were not very efficient in gas production and overall energy balances, and with apparently never-ending and cheap supplies of oil and other fuels there was no incentive to undertake systematic and long-term research and development to produce a proper plant.

Two things have lately changed the picture in agriculture and its related industries. In the older (but still practised) mixed farming systems animal production was related to the land available for disposal of the animal excreta as fertilizer. Farms were relatively small and so were quantities of wastes. Pollution from the wastes was little, if any, and localized. Biogas production from the small individual quantities of wastes, even if wanted, would have been small and it was not worth collecting waste from different farms to a central gas-production unit.

The introduction in the last 20 years or so of the 'intensive', specialist farm, or intensive unit to existing farms, and particularly the 'slurry systems' of waste collection used in intensive pig- and cattle-units, has changed the picture. These farms and units have hundreds, thousands, or even millions, of animals or birds kept in small land areas and the collection, storage and disposal of the excreta from these animals can cause pollution problems, especially in a world increasingly conscious of pollution and health hazards. And it was from the point of view of pollution control on such farms that the present author and colleagues started investigations on anaerobic digestion of agricultural wastes some 15 years ago. The large amounts of wastes involved in these farming operations made comparatively large-scale production of biogas possible, but the previously mentioned considerations applied and the biogas was thought of mainly as a fuel for running the plant and making the pollution control energetically and economically cheap.

The more recent realization that supplies of fossil fuels, particularly oil, are finite and that whatever the outcome is in terms of reserves the prices of conventional fuels will continue to rise, has changed the picture again. While pollution control remains a big consideration (although in many cases economically unquantifiable), present fuel prices have made it possible by using construction methods different from the conventional sewage plant to produce biogas at a price competitive with conventional fuels and which will pay for the digester plant in terms of a fuel source. The intensive farm is a big energy-user and has fuel needs and costs commensurate with this, but the numbers of animals in some cases are such that production of gas to supply not only the farm but towns and villages is possible. Development in countries like Britain is based on the biogas supplying energy for the farm and perhaps some houses or a factory in its locality; in countries such as the USA the much larger feedlot units could supply gas for more widespread distribution. But the picture is also changed in other countries where small, 'peasant', farming operates. Supplies of the conventional fuels such as wood, are decreasing and cannot be replaced by expensive oil. Biogas production on a small scale could provide a substitute fuel and a good fertilizer, and in passing one might mention that a conventional substitute for wood, the burning of dried animal-excreta, gives not only a poorer fuel than biogas but destroys the fertilizer value of the excreta.

Agricultural wastes of all kinds are a renewable feedstock for energy production, and because of demands for food the intensive farming units will continue in the future, so in the last few years research on biogas production has increased considerably.

The amount of information on biogas production has increased in the same way, and in a short paper such as this it is impossible to give a detailed description with bibliographical annotations of the microbiology of the process and of results of all the tests on various substrates, and of the engineering research which have been carried out. The bibliography to this paper suggests a few papers and books which can lead the reader more deeply into the subject and all that is attempted here is a short review of the overall state of research and development.

The reactions of anaerobic digestion

The reactions of anaerobic digestion are, as the name suggests, carried out in a highly reduced liquid under an atmosphere devoid of oxygen. The reactions are complex and a large and very heterogeneous population of bacteria is involved. But one of the properties of this mixed population is that, provided it is contained in a vessel to which the access of air is limited, some members of the population and their reactions can provide the highly-reduced conditions needed by other members. Thus no chemical reducing agents, or exacting precautions to keep air from the feedstock or digester, are needed. Although the individual bacteria when grown in laboratory pure culture are among the most exacting known, in the mixed population of the digester interactions and symbiotic growth lead to a stable population which can withstand many adversities. Since, as indicated before, the bacteria occur in many habitats, inoculation of a feedstock, to start the growth of the bacterial population, is not generally necessary. Fecal wastes contain the bacteria, although they are not in the correct proportions of the final digester population, so a stable digestion can be obtained by feeding the wastes slowly into a digester and allowing time, and the right conditions, for the correct population to develop. Purely vegetable-waste digestions can be started by addition of fecal wastes. On the other hand, as the bacteria develop in slurries of waste vegetable-matter, or the effluents from factory processing of vegetable matter of different kinds, digesters for these wastes have been started by using feedstock which has been allowed to stand in open ponds for some months and which has begun to decompose. Of course, a digestion will start off more quickly if the digester is inoculated from the contents of a digester already working on that feedstock, but, as it is not often possible to obtain such an inoculum for agricultural waste digesters, the previously-mentioned development of a digester flora ist the usual process used.

The microbial reactions in digestion can be divided into 2, or more generally 3, stages although, of course, in the usual digester these stages all occur at the same time and intermediate products are immediately further metabolized.

The digester feedstock, fecal or vegetable waste, contains polymeric carbohydrates, proteins and fats from the vegetation or residues of feed undegraded in the animal gut, or from the intestinal bacteria which make up a large proportion of feces, or from intestinal secretions. The carbohydrates are hydrolyzed to monomer or dimer units such as glucose, xylose, maltose, and proteins are split to amino acids some of which are then deaminated to give ammonia. Fats are split to give long-chain fatty acids and these are degraded to give acetic acid and hydrogen.

In the 2nd stage the sugars are fermented to produce mainly acetic acid, hydrogen and carbon dioxide. The fermentation reactions and possibly other reactions produce energy utilized by the bacteria to form new cells incorporating amino acid or ammonia nitrogen.

In the 3rd stage the acetic acid, hydrogen and carbon dioxide are converted into methane and carbon dioxide: the biogas.

This is only a very brief summary; many other actions and interactions involving salts and other components (non-protein nitrogen compounds, etc.) of the feedstocks take place, and the actual fermentation stage is not as simple as presented here. But these reactions lead to the feedstock being converted to gas, with the bacterial cells, organic materials unattacked or not completely degraded, grit, stones and other debris, forming in the water of the feedstock the digested sludge. In the process, polluting materials in the feedstock are converted to gas or relatively nonpolluting residues.

If the feedstock were a factory waste containing sugars and not polymeric carbohydrates then the initial hydrolysis step would not be needed and the feedstock would be directly fermented.

While the reactions occurring during digestion are known, the bacteria involved have not been completely identified, and details remain to be investigated. Microbiological investigation of digestion has developed from rumen microbiology and significant advances have been made only comparatively recently. Nevertheless, although digesters have been, and are being run and the practical details of breakdown of a particular feedstock can be experimentally determined without detailed knowledge of digester microbiology, the microbiological details are needed for, among other things, mathematical modelling and prediction of digester behaviour. Future application of microbiological data may bring about more efficient digester operation.

Types of digesters, and gas production

Digestion like any bacterial culture, can be done as a batch or as a continuous process. The role of batch digesters is very limited. As in most cases the feedstock is produced continuously (e.g. farm animal effluents) and energy demand is continuous, most digesters are run on a continuous basis. High-volume, low-solid-content, waste waters from food processing or other factories may require a feed-back ('contact') digester system and large-scale plants of this type are being tested in Britain and elsewhere. However, agricultural wastes are mainly animal excreta and/or vegetable matter and these are slurries of relatively high solids content. Just as for the sewage sludges the most generally applicable type of digester for these feedstocks is the single-stage, stirred tank. Other configurations such as the tubular digester are being tested, but the tank digester is being applied to all sizes of plants from the simple 2 or 3 m^3 digester of India or China to the hundreds or even few thousand m^3 automated digesters of the large farms or feedlots.

The large-scale, single-stage, stirred tank system consists, first, of a holding tank for the feedstock. In the case of animal excreta this tank may be under the animal house and be the sump at the end of floor, or under-floor, channels collecting the excreta from animal stalls or pens or, because of the arrangement of the farm buildings, be a separate tank near the digester with excreta pumped or flowing from the animal-house tanks. From the tank, the feedstock is pumped by an appropriately programmed pump to the digester tank. The digester is sized on the basis of the feedstock flow and the necessary detention time for digestion of the particular feedstock, and it is heated and stirred. Stirring is required only to ensure mixing in of the input and reasonable homogeneity of the tank contents, and is usually done intermittently for a short time every few hours. Mechanical stirring is used, but most large digesters now use some form of gas bubbling, the biogas being taken from the digester head-space and reinjected at the bottom of the digester. Heating is by warm water, usually passing through internal heat-exchangers of various designs, and coming either from a biogas-fired boiler or the cooling water of a biogas engine. The digester contents are removed at the rate of input feeding, usually by gravity flow over some weir or standpipe system which retains a gas pressure of a few inches water-gauge in the digester. The overflow then runs to storage tanks from where it can be distributed to fields as fertilizer, or treated in some other way. A small part of the daily gas production is stored either in a separate gas-holder or in a floating gas-holder forming the digester top.

There are many variations in detail on this basic design. The tank may be above or below ground, some digesters have pumped outflow, a few a gravity inflow, some are run at more than the few inches water-gauge pressure, and so on. The simple 'peasant-farm' digester is, of course, entirely hand- or gravity-loaded and unloaded, and hand-stirred, if stirred at all.

Digesters can be run in the 'mesophilic' range at temperatures usually about 30–42 °C, or in the 'thermophilic' range at about 55–60 °C or 65 °C. But the bacterial populations must be developed and stabilized for the operating range and within that range the temperature must be controlled as accurately as possible. While some laboratory-scale work has been done on thermophilic digestion and there are some advantages in rates of reactions in using this temperature range, there are energetic and other reasons for preferring the mesophilic range for most practical applications, so the greatest amount of research has been done on mesophilic digestion and most, if not all, practical digesters are running in this range.

The absolute amount of gas produced, and the methane content, varies with substrate, and the actual amount per digester volume/time unit depends on temperature, detention time, solids content and composition of feedstock, etc. In a short paper all the results for all the feedstocks which have been tested under different conditions cannot be given. However, the figure for piggery waste of 0.3 m^3/kg total solids (dry wt) fed to the digester, with gas of 68–70% methane content is, roughly, the kind of gas production expected from many agricultural wastes. As 1 fattening pig produces about 0.5 kg of fecal solids then 1000 pigs will produce approximately 150 m^3 of gas per day. This will have an energy value of the order of 1000 kWh.

While in a warm climate little, if any, heat will be needed to keep a digester at a mesophilic temperature, in a temperate climate artificial heating of a digester will be needed for most of the year. This heating is a debit to be set against the useful energy production of the digester. The heat may be taken from a biogas boiler which may also be linked to some building or other heating system. However, many agricultural-waste digesters are designed to run gas-engine generators and here waste engine heat can be used for producing hot water for digester, and possibly other, heating purposes. Some 25% of the fuel energy can be obtained as electrical energy and up to 65% more of the fuel energy can be recovered from engine and exhaust heat-exchangers. A very approximate figure of 30% of the biogas energy is usually used to suggest the heating requirements of a digester in a temperate climate, but this obviously varies.

The situation all over the world at the moment with regard to the bigger agricultural-waste digesters is one of development and testing. There is no difficulty about the microbiological side of the process; digestion once started is stable. What problems are being encountered concern the handling of the feedstocks, and sometimes on farms provision of feedstocks of suitable consistency and uniformity from day to day. Other aspects being tested are the life of the gas engines being used as these differ froœ the large dual-fuel engines which have been used for many years in most of the sewage works using biogas energy. The life of pumps and other components of the actual digester construction has still to be assessed. While some digesters are having more difficulties than others, many are now running successfully and a problem in some cases is to find uses for the energy being produced.

It is difficult to find out how many of the small-scale, 'developing country', digesters are continuing to run successfully, but there is no doubt that many are running. However, one of the problems here is to find a design cheap enough for the very poor farmer, as well as to improve the efficiency of the digesters.

While there remains research work to be done on optimum conditions for digestion of some feedstocks and, particularly, mixed waste feedstocks, testing of different digester designs, use of digested sludge for other than fertilizer purposes, and so on, digestion has now got into the large-scale testing and development stage and the next few years should see the number of working digesters increasing. Digestion is the alternative fuel source of most widespread possible application, using, as it does, almost any organic waste, and its ability to use fibrous vegetable matter is putting the energy-farm nearer practical application in countries where crop production and energy requirements of the population are suitable. Digestion can also be used in conjuction with other forms of bio-energy production to utilize vegetable residues from sugar or starch production – there are many possibilities now being or to be exploited.

Some books and review papers on anaerobic digestion:

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Possibilities of gas utilization with special emphasis on small sanitary landfills

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Summary. Based on general observations on gas production in sanitary landfills, properties of some important landfill gases are discussed, especially with regard to the potential heat recovery. It has been shown, based on practice oriented considerations, that the utilization of landfill gases can be worthwhile even in small landfills. A scheme has been given which shows all the possibilities for collection, pretreatment, storage and combustion of the gases. The question of energy storage and energy utilization has also been addressed. The scheme has been discussed, as well as some of the processes, using the example of the hot water generation plant in the Croglio sanitary landfill in Tessin (Switzerland).

Calculation of the running costs shows that this plant, which is designed for a 335 MJ/h production, is working economically.

The term 'refuse management' implies the re-utilization of materials and/or energy. It is very seldom however, that one encounters good examples for such re-use, especially when dealing with small refuse disposal areas.

Since even in small landfills (landfill volume up to