CHAPTER 4
How Biogas Works

Everybody involved in a biogas programme, especially the administrative and technical staff, should have a simple understanding of the biogas process. The details of anaerobic digestion are complex and require an understanding of biochemistry (see Gunnerson for a good introduction),[1] but a simplified account is useful.

Biogas is produced by certain types of bacteria: microscopic organisms that break down the complex molecules contained in the feedstock into simpler molecules in a way that releases energy and the chemicals they need for growth. The bacteria that are used in a biogas digester are the same or similar to those that live in the gut of ruminant animals, such as cattle. Cow dung is a good source of suitable bacteria. These bacteria are adapted to the conditions found inside a cow, so a biogas digester must have a similar environment. The key factors are the exclusion of air and light and a temperature close to blood heat (between 20°C and 40°C for the mesophylic bacteria used in rural plants).

These conditions can be met in a hole in the ground, lined with brick or cement to keep the mixture of bacteria, water and feedstock (called a 'slurry') from leaking out, with a suitable cover which excludes air and light and also collects the gas. In tropical and sub-tropical areas the ambient temperature is usually about right for biogas digestion during most of the year. In cooler climates, some method of insulating and heating the slurry is required.

4.1 The anaerobic process

Several different types of bacteria live in a biogas digester and do different jobs.[2,3] Bacteria are single-celled organisms surrounded by a membrane. They secrete chemicals, called *enzymes*, through the membrane into the food around them, to break it down into simpler substances. These substances will dissolve in water, so they can be absorbed and used by the bacteria.

There are several ways of classifying bacteria. Here it is useful to consider their response to oxygen. *Aerobic* bacteria require oxygen to survive, while anaerobic bacteria cannot function at all in the presence of oxygen (they do not die, they stop working until the oxygen is removed). *Facultative* bacteria are able to use oxygen if it is present, but can use alternative digestion processes if it is absent.

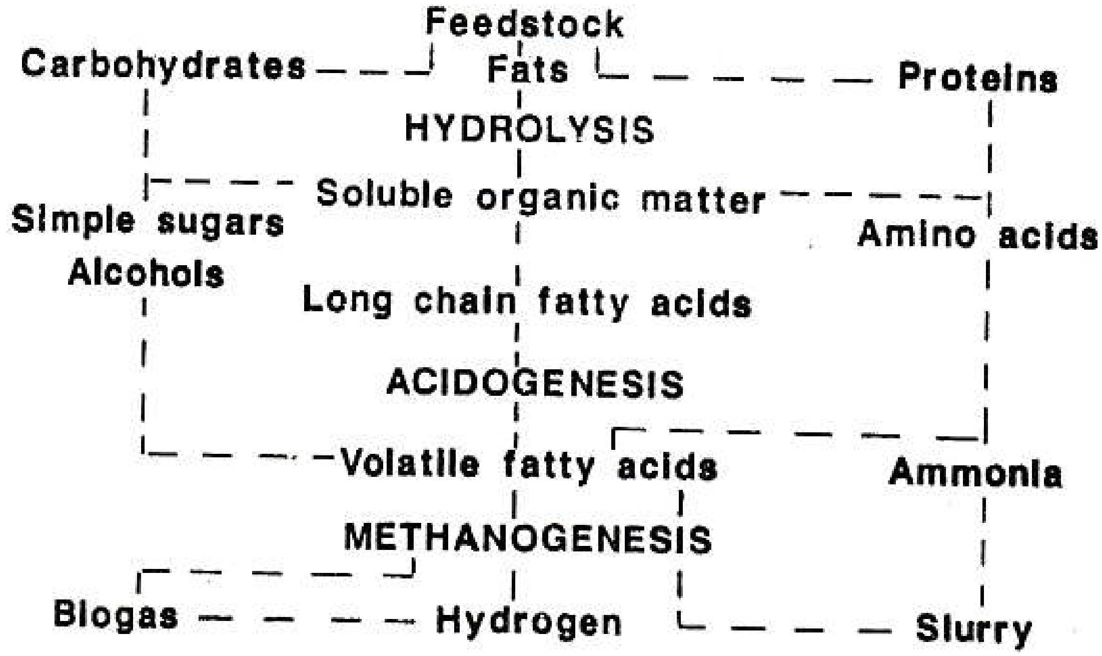

Figure 4.1 *The anaerobic process.*

When a feedstock is placed in an anaerobic digester the facultative bacteria begin to break down the complex molecules (Fig. 4.1), using up the oxygen in the feed. They will also use the oxygen in the air trapped inside the digester, thus lowering the gas pressure. These bacteria continue breaking down foodstuffs using oxygen from water once the free oxygen is finished, so this process is called *hydrolysis*.

The second stage (or the second half of the first stage, the *liquifaction* stage) is the formation of *volatile fatty acids* as well as carbon dioxide and some hydrogen. These acids are of low molecular weights and have low boiling points. Acetic acid (CH_3COOH), which is the major constituent of vinegar, is the commonest acid formed. If there is some air present the digestion process stops at this point, and the digester gives off the distinctive smell of these acids, usually associated with decaying food.

In an anaerobic digester (with no oxygen), the third stage, the *methanogenic* stage is continued by methanogenic bacteria which break down these fatty acids into even simpler molecules: water, carbon dioxide and methane (H_2O, CO_2 and CH_4), removing the smell and producing biogas. Methanogenic bacteria are *obligate anaerobes*; they cannot function if oxygen is present. Different methanogens are able to use a range of fatty acids as well as simple alcohols and even hydrogen and carbon dioxide to form methane. However, about 70 per cent of the methane in biogas is estimated to come from acetic acid ($CH_3COOH \rightarrow CH_4 + CO_2$).

The many different types of bacteria work together in a symbiotic relationship. The hydrolytic bacteria produce waste products that the acid formers can use. The acid formers, in turn, produce acids that the methanogens use, giving biogas as their waste product. If all the bacteria are working in balance the acid level remains constant, the rate of production by the acid formers equalling the rate of use by the methanogens.

4.2 Effect of pH

The measure of acidity is called *pH* (the negative logarithm, base 10, of the concentration of hydrogen ions; see Fig. 4.2). A normal value for pH in a working biogas plant is between 7 and 8 (about neutral). When a biogas plant is newly started, the acid formers become active first, reducing the pH to below 7 (increasing the acid content). The methanogens then start using these acids, increasing the pH back to neutral.

A working biogas plant is *buffered*, in other words, the acid level is controlled by the process itself. Some of the carbon dioxide (CO_2) produced by the bacteria dissolves in the water to form bicarbonate ions (HCO_3^-) which cause the solution to become mildly alkaline. The amount of bicarbonate in solution depends on the concentration of carbon dioxide and the amount of acids in the slurry. The effect of this carbon dioxide passing in and out of solution acts as a buffer to balance out small variations in the acidity of the slurry.

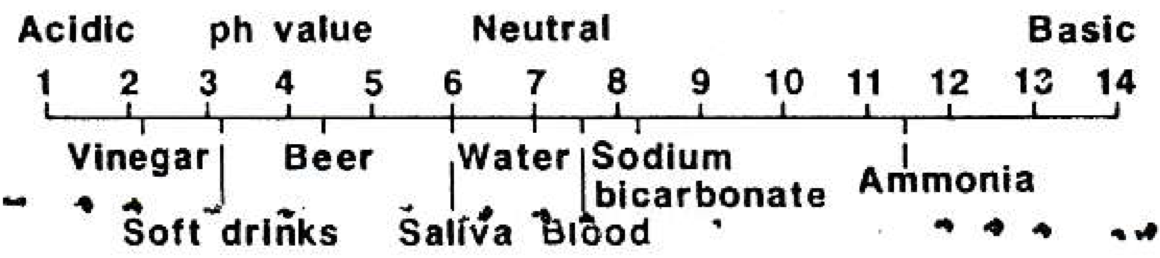

Figure 4.2 *The pH scale*

The pH of the slurry is easily measured using a pH meter or with suitable indicator papers. However, it is an insensitive measure of the way the digester is working, because of the buffering effect. If the pH of a digester drops it indicates the buffering mechanism has already failed and too much acid is being produced, usually because the methanogenic bacteria have stopped working for some reason.

A better measure of the stability of a digester is its *alkalinity*. The amount of bicarbonate in a sample of the slurry can be measured by titrating it against a known acid (see Appendix III).

4.3 Effects of temperature

Another way of classifying bacteria is according to their preferred temperature. *Cryophylic* bacteria work best at between 10°C and 20°C, *mesophylic* bacteria between 30°C and 40°C and *thermophylic* bacteria between 45°C and 60°C. While anaerobic digestion is very efficient in the thermophylic region, rural digestors use mesophylic bacteria because higher temperatures are difficult to maintain.

The gas production rate roughly doubles for every 10°C rise in temperature between 15°C and 35°C. The gas-production efficiency (the gas produced per kilogram of feedstock) also increases with temperature. A mesophylic digester works best at 35°C.

Methanogenic bacteria are sensitive to temperature changes. A sudden change of more than 5°C in a day can cause them to stop working temporarily, resulting in a build-up of undigested volatile acids: the plant goes 'sour'. This is less of a problem in large-volume digesters, where the high heat capacity of the slurry ensures that its temperature changes slowly.

4.4 Effect of toxins

The main cause of a biogas plant going sour is the presence of toxic substances. Antibiotics, disinfectants and pesticides are designed to kill bacteria and will stop a digester functioning, as will detergents. Chlorinated hydrocarbons, such as chloroform and other organic solvents, are particularly toxic to biogas digestion.

Care must be taken that the feedstock used in a biogas plant has not been affected by these chemicals and that the water used to mix the slurry is not polluted. The dung of any animals being given antibiotics should be kept separate and not added to the plant. If an animal shed is cleaned with detergents or disinfectants the washings must be directed away from the biogas plant. The chemicals used to clean the shed must then be washed away with plenty of water before the animals are allowed to return.

Methanogenic bacteria are not killed by toxins, but switch themselves into a non-working state.[4] Once this happens volatile acids build up and the plant begins to give off a bad smell. In principle, it is possible for a biogas plant to recover from this sour state if the pH is corrected using lime or chalk (calcium hydroxide or calcium carbonate) and the source of the problem is removed.[5] However, if the plant has been badly poisoned it may be difficult to remove the toxins without removing most of the bacteria. In this case, the digester must be emptied, cleaned with plenty of water and refilled with fresh slurry.

4.5 Properties of feedstocks

Any material containing food substances, such as fats, carbohydrates or proteins, can be digested in a biogas plant. However, the rate and efficiency of digestion of the feedstock depends on its physical and chemical form. Raw plant material is bound up in plant cells, usually strengthened with cellulose and lignin, which are difficult to digest. In order to let the bacteria reach the more digestible foods the plant material must be broken down.

Cattle dung is the easiest feedstock to use for a biogas plant: it already contains the right bacteria and it has been ground up by the animal's teeth and broken down chemically by acids and enzymes in the animal's gut. Human, pig and chicken manure are also good, but need a 'starter', such as slurry from a working plant, if they are used to start a biogas plant, because these animals do not have all the right bacteria in their gut. Some animals, such as horses and elephants, are less good at breaking down fibrous material, so their dung contains more indigestible matter. This can be screened out or chopped mechanically. Goat and sheep dungs are rich in nutrients,[6] but they are in the form of pellets that must be broken up mechanically. These pellets are difficult to collect, so there are few reports of their use in the literature.[7]

Raw vegetable matter usually needs to be treated before it can be used. It can be physically chopped up or minced, or it can be treated chemically.[8] Some plants, such as water hyacinth, have little lignin, so are easier to use. One good method seems to be to compost vegetable matter for five days before adding it to the plant, as aerobic bacteria are better at breaking down cellulose.

There are several measurements that can be made to define the properties of the feedstock or the slurry (Appendix III):

1 Total solids (TS) is a measure of the dry matter (DM) left after the moisture has been removed (by heating to 105°C).
2 Volatile solids (VS) is a measure of the organic solids lost when the dry matter is burnt (at 500°C or 600°C).
3 Chemical oxygen demand (COD) is a measure of the degree of pollution of the slurry. It is determined by chemically oxidizing a sample.
4 Biological oxygen demand (BOD) is an attempt to measure the pollution more realistically. Aerobic bacteria are used to digest the sample and the oxygen required is measured.
5 Carbon to nitrogen ratio (C:N) is an important parameter as anaerobic bacteria need nitrogen compounds to grow and multiply. Too much nitrogen, however, can inhibit methanogenic activity.

Typical values for some of these parameters are given in Table 4.1. These results depend very much on the size of the animal, what it is eating, the weather, etc. Hot dry weather will cause water to evaporate from the dung before it is collected, giving an apparent increase in TS, while humid weather will have the opposite effect. Measurements should be made of the properties of locally available feedstocks that could be used in a biogas

Table 4.1 Properties of dung from typical animals[9,10,11]

Animal	*Wet Dung (kg/day)*	*Biogas (lit/day)*	*Total Solid (%)*	*Volatile Solid (%TS)*
Buffalo	14	450–480	16–20	77
Cow	10	280–340	16–20	77
Pig	5	280–340	25	80
100 hens	7.5	420–510	48	77
Human	0.2	11– 14	15–20	90

programme and these values considered when suitable biogas plants are designed.

The total solid content of animal dung varies between 15 per cent and 30 per cent (Table 4.1), while the recommended value for slurry is between 8 per cent and 12 per cent. This means that dung must be diluted with water before it is used in a biogas plant. A low solids concentration mean that the digester volume is used inefficiently. It can also lead to separation of the slurry, the heavier solids sinking to the bottom to form a sludge layer and the lighter solids floating to form a scum layer on top of the liquid (supernatant). The scum layer can dry out to form a solid mat, preventing gas release from the liquid and blocking pipes. This should not happen if the TS of the slurry is kept above about 6 per cent.

A slurry with a high solids concentration (greater than 12 per cent) does not easily flow through inlet pipes. If toxins are present, such as a high nitrogen concentration, bacteria are more likely to be affected in a thick slurry. However slurries of up to 30 per cent total solids can be digested in a dry fermenter.[12,13]

The volatile solid content of dung is usually around 80 per cent of the total solids (Table 4.1). The remaining ash (fixed solids) is composed of soil particles, inert portions of vegetable matter (some grasses, e.g. rice, concentrate silica in their stalks) and some solid carbon left from the decomposition of foodstuffs. VS is not an ideal measure of the digestibility of a feedstock. Lignin and other indigestible solids will burn at 500°C, while some digestible solids, such as sugars, leave a carbon deposit when heated. It is an easy measurement to make (Appendix III).

COD and BOD are also not ideal ways to predict when proportion of the feedstock will be digested in an anaerobic digester, as they were designed as measures of the aerobic digestibility of materials. While they may give a more valid answer than VS, these measurements are much more difficult to make (Appendix III). The best way to determine the anaerobic digestibility of a feedstock is to digest it in small laboratory digesters (2 litres) in controlled temperature baths (see Appendix III).

COD is useful in that it is possible to define a value for methane. Using this figure, a digester should produce 350 litres of methane for each kg of COD digested.

The ideal C:N ratio is reported to be 25:1. The measurement of total carbon and nitrogen requires a well-equipped laboratory, but values of C:N are quoted in the literature for many feedstocks (Table 4.2) and the ratios for mixtures can easily be estimated from these values.[14] However, the values of total carbon can be misleading, as some of the carbon is bound up in indigestible lignin. The nitrogen content of plant materials varies with the age of the plant (e.g. barley straw contains 39 per cent protein at 21 days of growth, but only 4 per cent after 86 days).

Table 4.2 Carbon and nitrogen content of feedstocks

Material	*C:N*	*% N*	*% C*	*% Water*	*Comments*
Cattle dung	20–30	3–4	35–40	72–85	Grass/Grain fed
	25–35	1–2			Straw fed
Horse dung	25	2	58	70–75	
Sheep dung	20	3.8	75	68	
Pig dung	14	3–4	53	82	
Poultry dung	8	3.7	30–35	65	
Human faeces	6–10	4–6	40	75–80	
Human urine[15]	0.8	15–18	13	95	
Water hyacinth[16]	15–23	1–9	24–35	93–95	Dried
Rice straw[17]	47.2	0.6	40	5–10	

Notes: Data for fresh dung. All dung will lose water and nitrogen on keeping, especially if air humidity is low.

In general, the C:N ratio of dung from cattle fed with poor feeds, such as straw and dry grass, tends to be too high (up to 35 per cent). The values quoted in Western literature (20 per cent or less) are measured using dung from cattle that eat more protein-rich foods. If the C:N is high, then gas production can be enhanced by adding nitrogen in the form of cattle urine or urea, or by fitting a latrine to the plant. If the C:N ratio is low, for example if chicken manure is used as a feedstock, the addition of carbon, such as chopped grass or water hyacinth, can reduce the possibility of toxicity from too much nitrogen affecting the bacteria.

4.6 Types of digester

A biogas digester can be operated as a batch process or a continuous one. In a batch digester the waste is put into the plant, usually with a starter

(5 per cent to 30 per cent by volume), and the gas collected as it is given off. There is a lag time of between one and 14 days before the first gas is given off (depending on the slurry temperature and the amount of starter).[9] For the first day or two the gas will be mainly carbon dioxide. The gas production rate will rise to a peak and then fall off (Fig. 4.3). There may be subsidiary peaks in the gas-production rate as less digestible material becomes available to the methanogens.

The advantage of a batch reactor is that the feed can contain lignin and other indigestible matter, as it does not have to be fed through inlet and outlet pipes. A batch digester can be run at a high solids content (as a dry reactor), reducing the volume of water required. Since the gas production varies with time, several batch reactors are usually run together, started at different times, so that some are always producing gas.

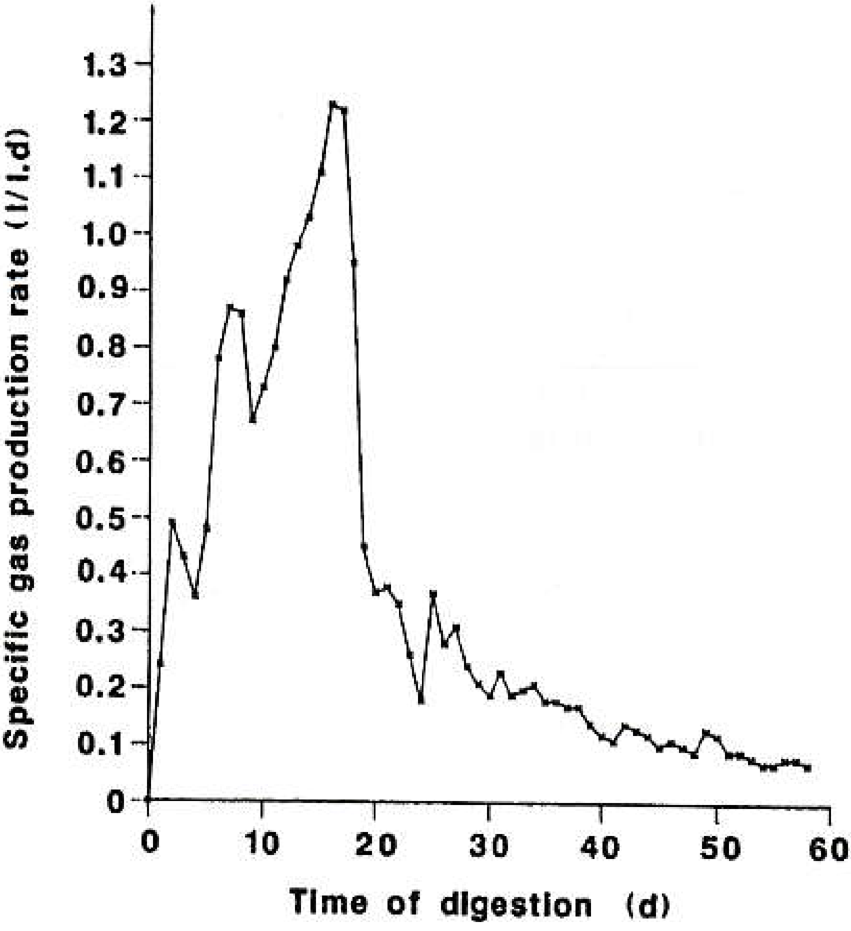

Figure 4.3 *Rate of gas production with time*

A continuous digester is fed regularly once it has been started. The feed is mixed with water outside the digester and fed through an inlet pipe. The outlet is arranged so that spent slurry either overflows into a collecting pond as new slurry is added, or it can be removed with a bucket. Once the digestion process has stabilised, the gas production rate is fairly constant (with constant feed rate and temperature). Care must be taken that the inlet and outlet pipes are not blocked by indigestible matter.

Many digesters in China are run in a semi-batch mode. They are started as batch digesters and filled with vegetable matter, such as straw and garden wastes, and animal dung and a starter. However these digesters are also fed daily, with dung (usually from pigs and an attached latrine) and vegetable wastes. The gas production remains fairly constant, as the daily feed is digested, but it is enhanced by the slow degradation of the less digestible matter. The Chinese empty these plants once or twice a year, removing the undigested materials and using the slurry as fertiliser on their fields. The disadvantage of this approach is the break in gas production during the time the plant is being emptied and restarted.

4.7 Digester design parameters

When a biogas digester is designed the main variable to be defined is its internal volume. The amount of gas produced depends on the volume of slurry in the pit. The digester volume is related to two other parameters: the retention time (R, measured in days) and the feed rate. For a batch digester, the retention time is simply the time the slurry has been left in the pit. For a continuous digester, it is given by the volume of the digester pit (V, m^3), divided by the volume of the daily feed ($V, m^3/day$):

$$R = \frac{V}{v} \text{ days.} \tag{3.1}$$

The volume feed rate (v) is given by the mass of total solids (m, kg) fed daily, divided by the proportion of total solids in the mixed slurry (assuming the density of feed is $1000 \ kg/m^3$):

$$v = \frac{m}{TS \times 1000} \text{ or } v = \frac{m}{TS\% \times 10} \ m^3/day \tag{3.2}$$

The retention time is always a compromise between gas production rate and efficiency. If the supply of feed is limited and the temperature low (less than 20°C), the retention time should be as long as possible (up to 100 days) to get the maximum gas from the feed. Long retention times also allow less digestible materials in the feed to be broken down. The volume of the plant will be large, though, making the cost high. If the feed is in plentiful supply and the temperature can be kept high (30°C), a retention time of 10 days is possible, giving a high rate of gas production. Special high-rate thermophylic reactors can have retention times down to one or two days, but these are very expensive to build and operate.

At low temperatures it is important to keep the retention time long, as the bacteria grow more slowly. If the bacteria are removed with the spent slurry faster than they can replace themselves in the digester pit, 'wash-out' occurs and the plant will fail. As the methanogens multiply more slowly than acid-forming bacteria, the main symtom of wash-out is the plant becoming sour. The plant may recover if feeding is stopped for a time.

The loading rate (r, kg.VS/m^3/day) of a digester is defined as the mass of volatile solids added each day per unit volume of digester. It is related to the mass feed rate:

$$r = \frac{m \times VS}{v} \text{ or } r = \frac{m \times VS\%}{v \times 100} \text{kg. VS/m}^3\text{/day} \quad (3.3)$$

Typical values for the loading rate are between 0.2 kg.VS/m^3/day and 2.0 kg.VS/m^3/day.

4.8 Effluent slurry

Anaerobic digestion not only breaks down plant materials into biogas, it also releases plant nutrients, such as nitrogen, potassium and phosphorous and converts them into a form that can be easily absorbed by plants.[18] These fertiliser chemicals are not removed or created in a biogas plant, although the removal of carbon, oxygen and hydrogen as methane and carbon dioxide means that the concentration of these other chemicals is increased (Table 4.3). For example, protein and amino-acids in the feed-stock are converted into ammonia, which forms soluble ammonium compounds with the fatty acids.[19]

While the value of biogas effluent as a fertiliser is well-known to biogas workers, most biogas programmes have given it too little emphasis. Farmers tend to assume that the removal of one benefit (biogas) from the feed must reduce its effectiveness in other directions (as a fertiliser). This attitude prevails even in China, where the people have a long tradition of composting wastes (especially night-soil)—despite intensive propaganda on the benefits of biogas.[21,22] Few Indian and Nepalese farmers, are convinced of the fertiliser value of the effluent, except those who have tried it and have become impressed with the results. One such farmer claims to be saving 80 per cent of the urea he used to put on his crops. A few institutions in India run biogas plants purely for the fertiliser they produce.

Table 4.3 Plant nutrients in air dried manure and effluent measured in Nepal[20]

Material	*Nitrogen %*	*Phosphorous %*	*Potassium %*	*Indigestible ash %*
Buffalo dung	1.01	1.11	0.92	26.43
Biogas effluent	1.41	1.18	1.48	28.64

Biogas slurry must be used correctly for its full value to be realised. Preliminary trials of slurry in Kathmandu, at the Department of Soil Science and Agricultural Chemistry, suggested that the concentration of nitrogen in the slurry was too high for transplanted rice seedlings, which grew too fast and weakened. The presence of hydrogen sulphide may be toxic to some plants,[9] especially when pig dung is used as a feedstock. However, frogs were able to live happily in the slurry pits of Nepalese biogas plants using cow dung as feed, so this may not be a major problem.

If biogas slurry is used carefully it does make an excellent fertiliser and soil conditioner. It is free from odour and does not attract flies. Most of the harmful bacteria and parasites in the original feed are either killed or considerably reduced in number.[23,24] The benefits of slurry use build up over several years. Tests in China show a productivity increase in rice production of 11 per cent to 14 per cent after biogas slurry had been applied to the fields regularly for four years.[19,25]

The major problem with effluent slurry is transporting it to the fields as it is in liquid form. Chinese plant owners often collect the slurry daily in buckets and carry them to nearby vegetable plots. Slurry has a total solids content of about 8 per cent, so 92 per cent is water, which is bulky and heavy to carry over long distances. A large volume is required to get an adequate quantity of fertiliser.

The usual practice in India and Nepal is to collect the effluent in shallow ponds and allow it to dry in the sun. This reduces its weight and volume considerably. Any toxic substances, such as hydrogen sulphide, evaporate and any remaining harmful bacteria are killed. However, ammonia is also lost by evaporation into the air and by leeching, as water drains into the soil. The loss of nitrogen from dried slurry (7 per cent to 15 per cent)[26] appears to be less than from drying raw cattle dung (20 per cent to 45 per cent).[6] However, sun drying takes up a lot of space and is difficult in the rainy season.

Digested slurry can be introduced into irrigation canals, so the water washes it to the fields. This approach was used in a biogas irrigation scheme in Parwanipur, Nepal.[27] Unfortunately, more slurry was deposited near the sluices from the canal than reached the far ends of the fields. Slurry can be put in tanker trailers and pulled by animals or tractors. In some communes in China, the slurry is then sprayed onto the fields, using a small biogas-powered pump.[25] This approach requires machinery and is expensive.

Slurry can be added to dry plant material, such as straw or leaves.[26,28] The dry material absorbs the plant nutrients and water and conserves them. The slurry contains facultative bacteria that composts the plant material, increasing its fertiliser value.

4.9 Research on microbiology and slurry use

Since the anaerobic process is complex, a biogas extension programme needs to have available the skills of a qualified microbiologist or biochemist as well as the services of well-equipped laboratories and trained personnel to run them. The digestibility of different local feedstocks needs to be tested and the causes of any plant failures discovered. A large programme might have its own laboratory and staff, but most biogas programmes employ university or government research laboratories on a consulting basis, paying for research and test work as required. In India and China, as well as other countries such as Thailand, the Philippines and Brazil, there are many research institutions involved in biogas-related research projects. In less-developed countries, special research programmes may need to be funded to ensure that specialist help is available when needed by the extension programme.

Much more work needs to be done on the use of slurry as a fertiliser. For example, a low-cost appropriate technology is required that can separate the solid from the liquid fractions of effluent slurry. The liquid can be used on nearby vegetable plots, leaving the less bulky solids to be collected and used on crops in more remote fields.[29]

A biogas extension programme should also have land available, either its own or loaned by agricultural research stations, on which the use of biogas slurry on local crops can be tested. These plots would also serve as demonstration and training areas to teach local farmers to make the best use of the fertiliser from their plants.