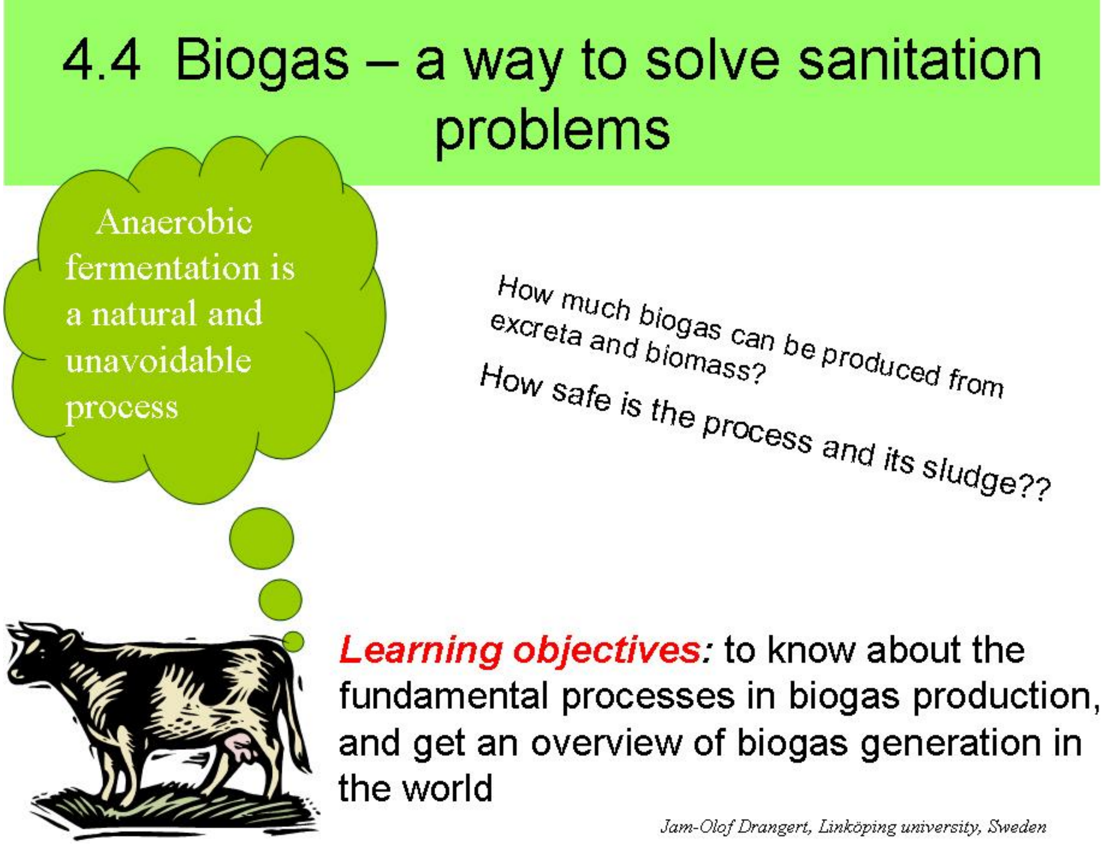


Energy from the sun drives the **water** (hydrological) **cycle,** lifting water molecules from the surface of the earth to clouds. The resulting rain and snow flows to lowlands by gravity and we can harness its potential energy and convert it to hydroelectric power or use it directly via water wheels. The sun also drives **photosynthesis** which makes the building blocks for plants and trees. The stored solar energy can be released again by burning firewood or oil and natural gas. Oil and gas are the result of biomass which was left to putrefy for millions of years.

Today, we can shorten the storage time from millions of years to just weeks by managing our organic waste in a more efficient way. At the same time we can solve a serious solid waste problem, since organic waste makes up more than half the volume of solid waste. The simple idea borrowed from nature is to feed organic wastes including excreta and manure into an anaerobic biogas digester. The generated gas is used as an energy source and the digested residue (slurry and sludge) can still be used as a fertiliser.

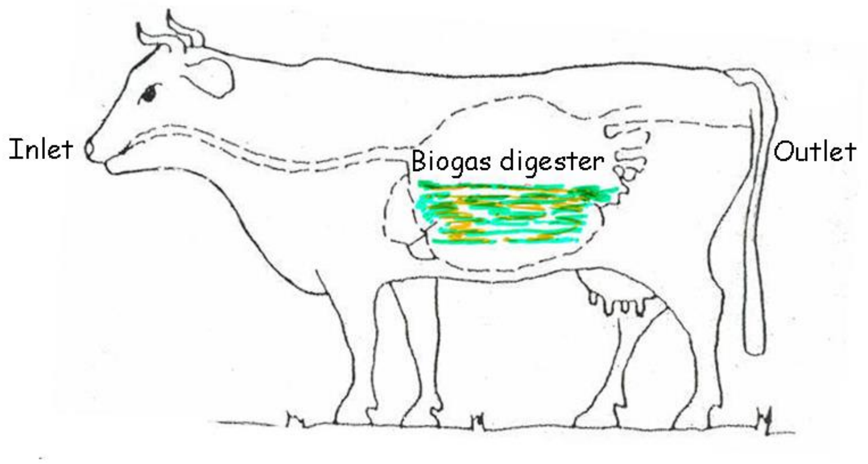
Biogas is gaining in popularity in Asia and parts of Europe. People need energy for cooking where firewood is scarce, and for lighting where there is no electricity and kerosene is expensive. The huge volumes of food waste, animal manure and human excreta, and some of the garden waste can be reduced substantially, while producing the biogas. Also, the slurry is rich in nutrients and can be used as a fertiliser. Thus, biogas should be considered in any discussion about sustainable environmental sanitation. More information is available at www.gc21.org This website “Global Campus 21” is hosted by Borda.

In this module we provide basic knowledge about fermentation and technologies to enable the introduction of decentralised biogas digesters. As discussed in the greywater modules 4.5–4.7, treatment and recycling is safe if households refrain from disposing of hazardous items in the wastewater or organic waste collection unit.

Pedro Kraemer, Borda-India and J-O Drangert & J. Ejlertsson, Linköping University, Sweden,

Spying on Nature – What can we learn from cows?

4.4 - 2



Cows convert biodegradable plants and water to milk, cow dung and urine – and gases

Pedro Kraemer, BORDA, Indi

Some characteristics of the cow's digestive tract are: there is no or little oxygen (air), the temperature in their stomachs is high and stable, there is plenty of water, and the material moves through four stomachs and guts in 30–36 hours. A cow may eat some 15–25 kg dry biomass, and excrete 40–60 kg of dung and 30–70 litres of urine per day. In order to survive, and produce meat and milk, the cow also needs nutrients such as iron, sodium, calcium, cobalt and nickel. Most of the nutrients are found in the milk and urine, and therefore free-range cattle distribute the urine nutrients rather evenly, while farmers try to collect and plough in the dung and urine from stall-fed animals. The dung is only partly decomposed biomass and its nutrients are readily available to plants.

The cow is only interested in the energy that is produced when the biomass is broken down in its stomachs, and not the simultaneously released gases through the cow's mouth, farted gases from its anus, and from excreted manure. A cow releases some 300 litres of methane gas into the atmosphere every day (http://www.g-o.de/dossier-detail-163-6.html) and ideally, we should trap this gas and use it productively. Gas is mainly formed in the rumen, which is the first of the cow's four stomachs.

Here, grass and other fodder are broken down and fermented by microorganisms into a wide variety of fatty acids (acetic, propionic, lactic, butyric acid etc), hydrogen and carbon dioxide. The fatty acids are assimilated by the cow through the rumen wall and transported by the blood for essential cell functions. More than 30% of the energy supply to a cow comes from the fatty acids generated in the rumen. In the rumen, anaerobic microorganisms multiply during fermentation and these organisms together with remaining fodder are digested in the following three stomachs and absorbed by the cow. The microbial biomass formed in the rumen is essential for the cow's uptake of amino acids and provides 60–90% of the absorbed raw protein together with vitamins such as cyanocobalamin (vitamin B12).

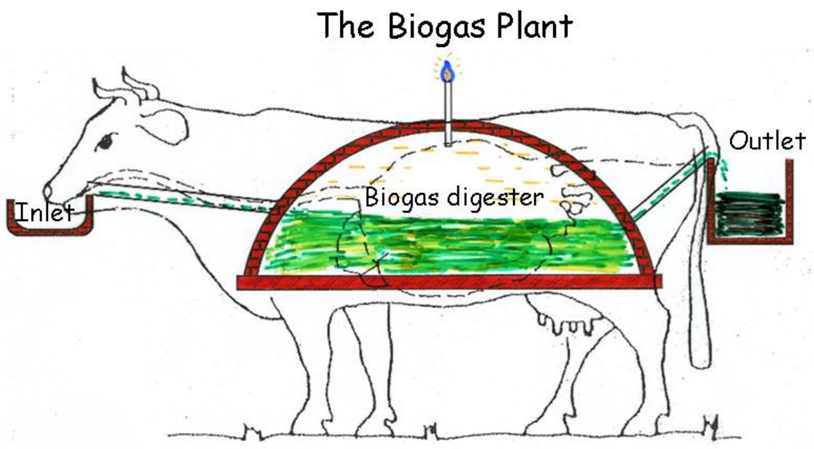
From a biogas perspective the reactions occurring in the rumen are most interesting. Hydrogen serves here together with carbon dioxide as food for methanogenic organisms that convert four moles of hydrogen and one mole of carbon dioxide to one mole of methane and two moles of water. The production of methane in the rumen is very important for the cow since it reduces the volume of gas that would otherwise have to pass out of its mouth. The process can be explained by the following example: Fermentation of 1 kg of sugar (glucose) gives rise to 489 g of butyric acid, 280 litres of hydrogen (22 g) and 280 litres of carbon dioxide (489 g). The formation of methane from the hydrogen and carbon dioxide reduces the total gas volume by 50% from 560 litres (280 litres hydrogen and 280 litres carbon dioxide) to 280 litres (70 litres of methane and 210 litres of carbon dioxide. However, even though this process is essential for the cow because it reduces the volume of gas that the cow has to deal with, the loss of methane is also a loss of potential energy. Research today has partly been oriented towards letting other microorganisms in the rumen convert hydrogen to something useful for the cow, such as acetic acid from hydrogen and carbon dioxide. A company in the UK is manufacturing a garlic derivative (Mootral) which reduces methane production by 15–20 % and raises milk production be 1.5 litres per day (bbc.worldchallenge.co.uk in 2009).

The volume of biogas created by ruminants (animals with a rumen) is in fact, so great that they contribute a large proportion of the 18% of global greenhouse gas emissions for which the livestock industry is responsible – causing global warming! A Japanese study found that the production of one kilogram of beef involves the production of greenhouse gases with a warming potential equivalent to 36.4 kilograms of carbon dioxide. The production of one kilogram of beef also releases fertilizing compounds equivalent to 340 grams of sulphur dioxide and 59 grams of phosphate, and consumes 169 megajoules of energy (Ogina, 2007). The study did not include emissions from farm infrastructure and transportation of the meat, so the total environmental load is even higher than the study suggests.

Cows also produce some heat in their stomachs, using oxygen that comes with the fodder or is supplied by the cow via its stomach wall. Cows can therefore utilise the reactions in their rumens as a tool to regulate their body temperatures. Also, human bodies release heat and carbon dioxide due to cellular activities and small amounts of methane from microbial digestion processes in the faeces. A dairy cow drinks some 30–200 litres of water every day, and produces 5–40 litres of milk. A bull drinks some 40–100 litres of water, but produces no milk. Since bulls and cows urinate about the same volume, they both need this large amount of water for digestion. We will later discuss why this is so.

A new look at the cow – and bull

4.4 - 3



Pedro Kraemer, BORDA, India

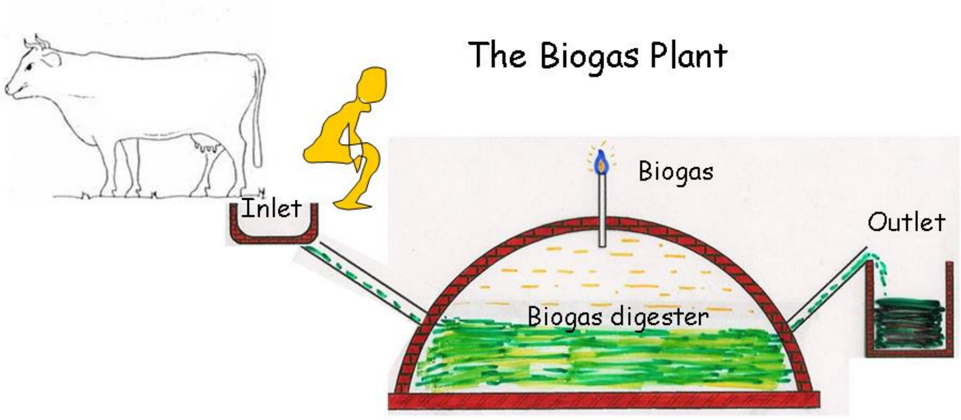
Technology often mimics nature, and by learning under what conditions cows digest grass, we may copy and control a similar process. If we view the stomachs of a cow as a biogas digester we will find several prerequisites for biogas production. In order to function properly, we need to ensure the biogas process has a relatively stable temperature, digestible organic material, and nutrients. The cow is a fantastic fermentation factory (see picture). However, there is an essential difference between a cow and a biogas digester. The fatty acids generated in the rumen are absorbed by the cow, and only a small amount of methane gas is released. In the biogas digester the fatty acids are converted into methane and carbon dioxide.

Digestion means that plants and other organic matter are broken down into smaller components. The original Latin word *digere* means scatter, disperse or dissolve. Such a process is called aerobic when it occurs in the presence of air (and molecular oxygen), and anaerobic when digestion occurs without molecular oxygen. The organisms that operate under anaerobic conditions originate from the first life forms on our planet some three billion years ago. Two billion years ago, when cyanobacteria first managed to absorb energy from sunlight and create molecular oxygen by photosynthesis, the environment became aerobic – an environment which was (and still is) poisonous for anaerobic organisms. The anaerobes then had either to adapt (mutate) to be able to survive in the aerobic environment in order to stay in the remaining anaerobic environments or die. That is why these fantastic creatures can still be found in sediments, marshlands and peat bogs but also in termites, ruminants and landfills.

In human beings and other aerobes, organic matter is degraded or transformed to serve as building blocks for cell material and to generate energy. Digestion is an oxidation process that produces carbon dioxide from the organic material and reducing power (see 4.6-20). In aerobes the reducing power is utilised to generate useful energy for the cell during the reduction of molecular oxygen to water. This digestion process is almost the opposite of photosynthesis in plants in which the energy in the sunlight does two things: 1) it generates energy and 2) it splits water into reducing power and molecular oxygen. The plants use the reducing power and carbon dioxide to form organic molecules and then to synthesize cell material by using generated energy, water and nutrients.

A biogas plant operates through anaerobic digestion of organic material

4.4 - 4



Pedro Kraemer, BORDA, India

We now try to mimic a cow stomach with a structure made of bricks and mortar, which we call a biogas plant. Its central component is the anaerobic biogas digester (see picture).

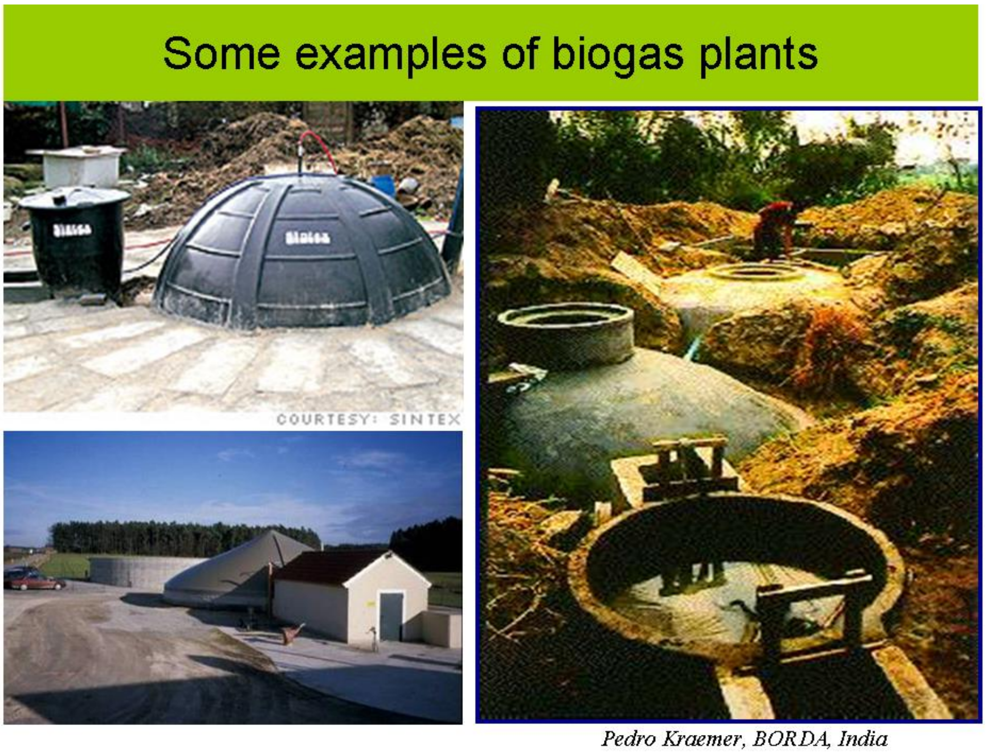
To replicate four features of a cow's stomach in the digester we need to: i) keep a stable temperature, ii) ensure that essential nutrients are available, (iii) ensure that enough water is available and, iv) ensure an oxygen-free environment. If the ambient temperature varies a lot over the year or between night and day, the digester must be insulated or just built underground as is done in China.

Any biodegradable organic matter is suitable for feeding the digester, except material containing a substantial amount of lignin, e.g. wood. High levels of organic matter are found in organic waste and wastewater from households, communities, and industries, as well as sludge and source-separated solid organic waste from industries, markets and restaurants, human excreta and agriculture. Suitable microorganisms are usually present in the organic mixture especially in sewage sludge and manure and do not need to be added. If industrial waste is toxic, it may be bad for the microorganisms and may prevent the use of sludge as fertiliser.

Ideally, a watery liquid is preferable for the digester with a mixture of organic material and water that contains 10% dry matter. What happens if dry-matter content deviates and how to remedy is discussed later in this module. Human faeces contain about 80% water and 20% organic and inorganic material, while urine contains 94 % water and only 6% organic and inorganic material. It is not enough to only feed the digester with human excreta, because it contains too little carbon (energy), and other organic material must be added.

A Chinese rule of thumb is that a small biogas plant requires dung from at least six pigs to produce enough gas for one household. Cattle dung (urine and excreta) contains roughly 12% dry matter and requires another 20% of added water to reach ideal dry matter content.
The addition of human excreta and household wastewater is a bonus from a process point of view.

4.4 - 5



There is a wide variety of biogas reactors from household versions to large units serving large communities. They all work on a common principle. Anaerobic bacteria break down organic matter at suitable, stable temperatures, mainly into CO_2 (carbon dioxide) and CH_4 (methane). A combustible mixture of CH_4 (50–75 %) and CO_2 (25–50%), commonly referred to as biogas, is generated in the air-less digester – leaving behind digested slurry, only partially hygienized, and a reduced volume of organic matter.

A digester for household use made of plastic (upper left) is said to convert the waste generated by a four-person family and provide enough gas to cook all meals. The manufacturer estimates that 2 kg of organic material supplies 0.5 kg of methane gas. The slurry can be used to fertilise the garden. The Indian government recently agreed to subsidise about a third of the cost for this type of family-sized unit (www.sintex.in; ARTI, 2011).

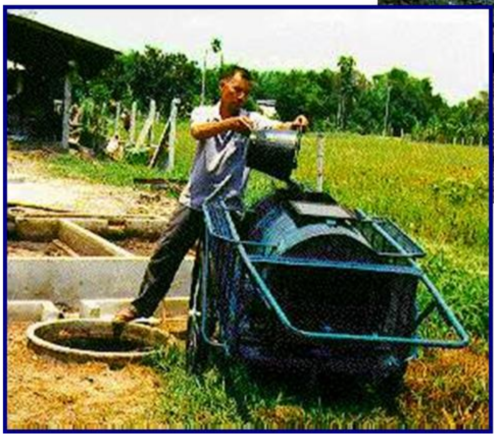
A common large biogas plant (bottom left) comprises a circular concrete insulated digester and a canvas tent to store the biogas. Such digesters are found in Germany and are fees by organic waste from urban restaurants and stallfed cows. The gas is utilised in a gas engine to generate electricity for sale to the electric grid.

The right-hand picture shows an underground biogas plant under construction. It has a fixed dome-shaped digester. The feeder is in front, and the slurry tank in the rear. There are millions of such biogas reactors in rural China, and also a number of advanced biogas plants in Japan processing vast amounts of human excreta.

We are now far away from the cow’s stomach and the emission of some 300 litres of gas every day. But, the digestion processes are similar.

Slurry application in agriculture

4.4 - 6



Pedro Kraemer, BORDA, India

The use of slurry or digested residue from the gas production depends on many factors like soil, climate, crop and common agricultural practices. Much of the nutrients in the residue have been mobilised and made plant available without further transformation by soil microorganisms. However, since part of the nitrogen is present as ammonium there is a risk of ammonia evaporation at dry and windy conditions. Fortunately, simple techniques used for soil application can keep the loss of nitrogen and other nutrients in the liquid slurry to a minimum.

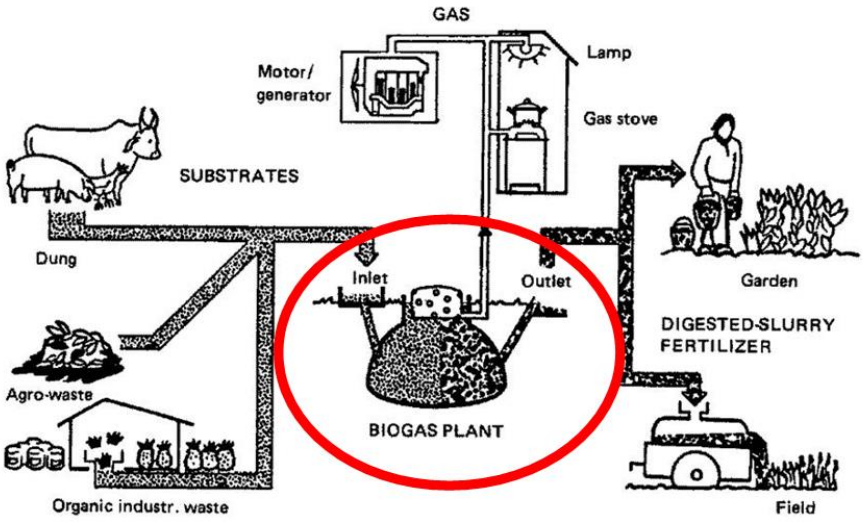
The liquid can be taken out of the digester by bucket (see left picture) or with a pump, since the dry matter content is only 0.5–1.5%. This very low dry content also makes it possible to spray the slurry in the field with conventional equipment (see right picture). Such combined irrigation and fertilising practice is favourable for permanent plantations, in particular if the wastewater was not mixed with industrial wastewater before digestion (see Module 4.5).

A typical fertiliser requirement is some 80 m^3 of slurry per hectare, which equals to 8 litres per square meter. For instance, fodder grass production yields some 50 tonnes per ha per year depending upon climate and growth period. A cow requires some 18 tonnes of fodder grass per year and therefore a hectare can carry almost three cows. Each cow produces a slurry volume enough to fertilise 1,500 m^2 and the three cows will provide slurry for half a hectare. Additional fertiliser is needed if nutrients are removed by milk and meat production.

Another solution is to compost the slurry and use it for seasonal crops. Such use entails significant losses of nitrogen, is a labour-intensive practice, but provides a good soil conditioner with long-term fertilising effect. Another positive aspect is that the weight of the composted slurry is small and so it is easy to handle during application. The application of composted slurry, on the other hand, may cause high losses of nitrogen.

Integrating biogas in agriculture

4.4 - 7



Pedro Kraemer, BORDA, India

A biogas plant is part of a larger system. It can be fed with substrates from various sources such as manure, agricultural waste, organic waste from households, restaurants etc. (left). The gas can be used to run stoves and lights, electric generators and be upgraded to vehicle fuel wherever needed. The gas has a high ignition temperature and is therefore perfect for combustion engines.

The digestive residue which is left after digestion can be used to fertilise gardens and fields, preferably after some hygienization. Health risks associated with biogas production are dealt with in Chapter 3. Caution needs to be exercised when inspecting or repairing the digester since remaining gas can explode or suffocate personnel entering the digester.

The digester provides multiple environmental benefits. It converts organic “waste” into useful products instead of causing a hygienic nuisance in communities. Trapping the gases from the digester reduces emissions of greenhouse gases as well as eutrophic discharges to water bodies. The slurry can replace chemical fertilizers manufactured in polluting processes (see 5.1).

We will perform a systems analysis at the end of this Module with an example of a biogas plant in a periurban setting.

Where is biogas technology applied?

4.4 - 8

Approximate numbers of biogas units in selected countries:

Country	No of units	Volume >100 m^3
China	12,000,000	x0
India (in 2004)	3,600,000	?
Nepal (in 2007)	200,000	?
Vietnam, Thailand, Tanzania, Bangladesh, Burundi, Brazil	x,000	3,400 (2006) in Germany
Kenya, Mexico, Cuba, Guyana	x00	?
Morocco, Ghana, Zimbabwe, Nicaragua, Jamaica, Bolivia	x0	DK, NL, S, Thailand,

99% of all systems do not use pumps, agitator, and heating

Pedro Kraemer, BORDA, India

In Asia and in developing economies in general, most digesters are for household use and are constructed with appropriate robust technology which is easy to operate. The leading nation is China with more than ten million small biogas reactors in rural areas. Over the decades, the Chinese have built up diverse know-how in the construction and utilisation of digester plants, and they are mainly motivated by the production of gas for energy. Likewise, governments in India and Nepal promote small units in rural areas.

European biogas digester development started in the 1930s as a means of reducing the amount of wastewater sludge. Later on it became politically driven with the aim of reducing emissions and the gas is used to generate heat and electricity as well as for the production of vehicle fuel. Today, the aim is to strengthen the renewable energy sector. The table above shows that most digesters are small units, except in Germany which has thousands of digesters with volumes of more than 100 m^3.

A lot of research and technology development takes places, especially in Germany and Denmark where digester technology has reached an advanced stage. For example, egg-shaped thermophilic digesters (see slides 4.4-14 and 4.4-25) with a heating system, agitator and gas purification are constructed to achieve high gas yields. In Europe biogas digesters are expensive and have high capacity and often take the feed from a variety of sources such as restaurants and animal stables.

Available human excreta in India compared to the need of fertiliser

4.4 - 9

Excreta viewed as waste:

Faeces	250,000 tons/day
Urine	1,000,000 m³/day

… or as a resource

		N-P-K:
Dry org. matter (**DS**)	90,000 t/day	
Nitrogen (**N**)	15,000 t/day	X
Phosphorus (**P_2O_5**)	5,000 t/day	Y
Potassium (**K_2O**)	3,000 t/day	Z
Carbon (**C**)	35,000 t/day	
Calcium (**CaO**)	5,000 t/day	R
Potential **biogas**	50 mil m³ day	

Pedro Kraemer, BORDA, India

Human excreta are rich in organic material and therefore a potential candidate as feed to biogas digesters. This example above from India shows the amount of human faeces and urine being produced every day. The content of the excreta in terms of various nutrients can be translated into fertiliser values. With a fertiliser mixture of nutrients in the common proportion $N:P_2O_5:K_2O$ = 1:0.5:1, it is possible to use all the 3,000 tons of potassium, the limiting nutrient in the excreta, to produce 7,500 tons of this fertiliser per day. There would be huge amounts of excess N (12,000 tons a day), as well as excess phosphorus (3,500 tons a day) to be used to manufacture additional fertilisers (Sasse, 1999).

The 7,500 tons of fertiliser per day would add up to some 2,700,000 tons per year of a complete fertiliser. This fertiliser is as effective as commercial fertilisers and much cleaner. We may compare this with the actual daily imports to India of fertilisers (annual import divided by 365 days): 844,000 tons of $(NH_4)_2HPO_4$ (diammonium phosphate) and 68,000 tons of urea. The amount of nutrient will basically be the same – if you digest a waste and faeces slurry, the organic content will be less (it leaves as gas). Nutrients like N and K will be set free. So if the digested slurry is not dewatered all nutrients remain in the slurry. And they are readily taken up by plants.

At sewage treatment plants the digested slurry is dewatered – thus lots of nutrients are lost via the water phase leaving mainly P in the digested residue.

In a later slide (4.4-13) we deal with the biochemical processes involved in gas production. The biochemical reaction is mediated by microbes in the absence of molecular oxygen. As a general rule the biogas process consumes water during the complete conversion of organic matter to methane and carbon dioxide.

Energy balance – for composting and digestion

4.4 - 10

Aerobic conversion (*composting*):

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$
$$\Delta G = -3{,}880 \text{ kJ/mol}$$

Anaerobic conversion (*digestion*):

$$C_6H_{12}O_6 \rightarrow 3CO_2 + 3CH_4$$
$$\Delta G = -405 \text{ kJ/mol}$$

Burning of biogas:

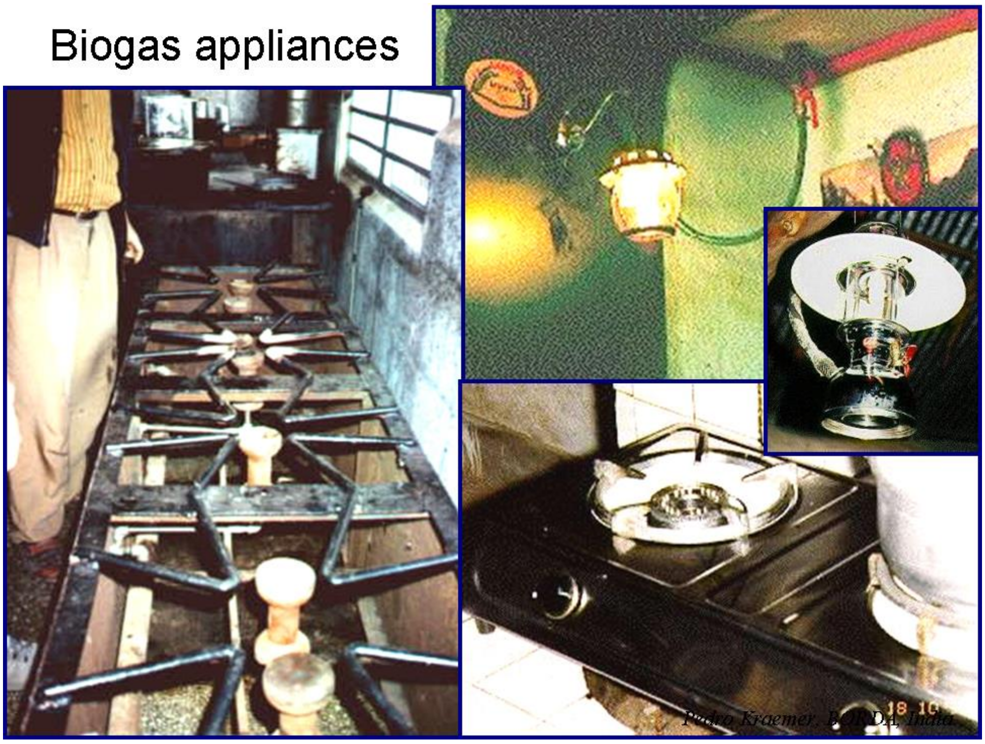
$$2CH_4 + 6O_2 \rightarrow CO_2 + 6H_2O$$
$$\Delta G = -3{,}475 \text{ kJ/mol}$$

Pedro Kraemer, BORDA, India

Energy cannot disappear; it can only be converted to other forms of energy of higher or lower entropy. The sun provides the energy for a photosynthesis which builds sugar molecules from water and carbon dioxide in the air. The sugar molecules are in turn building blocks for other organic compounds. In this way the sun energy is transformed into chemical energy and contained in the biomass. We now compare how this chemically bound energy is transformed in the two processes of aerobic composting and anaerobic digestion.

Compost. In conventional composting **aerobic** bacteria break down organic molecules such as sugar with the help of oxygen (air) to produce water and carbon dioxide (see formulas above). The released chemically bound energy (3,880 kJ/mole) is utilised by microbes which need energy to degrade the biomass. Excess energy that microbes do not need, heats up the compost heap. A high temperature in the heap helps to kill pathogenic microorganisms and if the temperature is high enough over a certain period, the compost heap will become hygienized (see Module 4.3).

Digester. In contrast, the **anaerobic** microorganisms in the biogas digester release very little energy (405 kJ/mole) when sugar converts into carbon dioxide and methane. Most of the chemical energy is contained in the methane molecules (CH_4) and is released only when the biogas is burnt. The residues are again water and carbon dioxide, which is used in the photosynthesis to build new organic matter. One of the favourable aspects of biogas is that it can be moved easily from the digester to any nearby place where it is needed for heating or lighting (next slide).



4.4 - 11

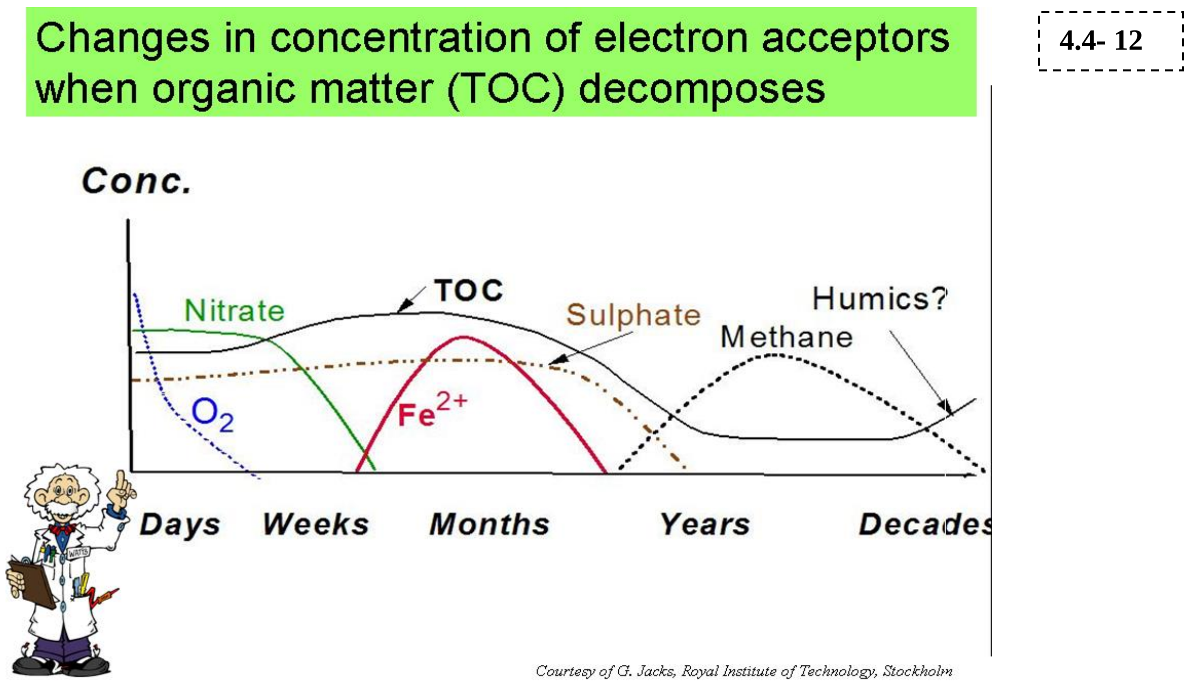
A good thing with the low pressure biogas is that it allows transport of the gas in a plastic pipe to the place where it is to be used. Unfortunately, the low pressure reduces the efficiency of technical appliances in the kitchen, even if they are properly designed. For instance, the efficiency of a biogas lamp is only half of the efficiency of a kerosene lamp due to the low gas pressure. Another example is that a fairly good burner has only just over 50% efficiency. The poor efficiency is compounded by abrasion of stoves and lamps.

Parameters affecting the efficiency are: the air-biogas mixture, the design of the burner including the geometry of the mixing chamber, the diameter of the jet, the diameter and number of burner outlets, the distance between outlets, and the distance between the burner head and pot. The table compares efficiencies of some common cooking fuels.

Table 4.4-11 Comparison of efficiency of cooking fuels.

Unit	**Fuel**	**Energy value**	**Efficiency**	**Net energy value**
kg	Cattle cake	2.5 kWh/kg	12% open fire	0.3 kWh/kg
kg	Fire wood	5 kWh/kg	12–16% better stove	0.75 kWh/kg
kg	Charcoal	8 kWh/kg	25%	2.0 kWh/kg
kg	Butane (LPG)	13.6 kWh/kg	60%	8.2 kWh/kg
m^3	Biogas	6 kWh/ m^3	55%	3.3 kWh/ m^3

Low efficiency is normally accompanied by more emissions of unburned methane. This is a serious problem since methane is a greenhouse gas that is 25 times more powerful than carbon dioxide (IPPCC, 2007).



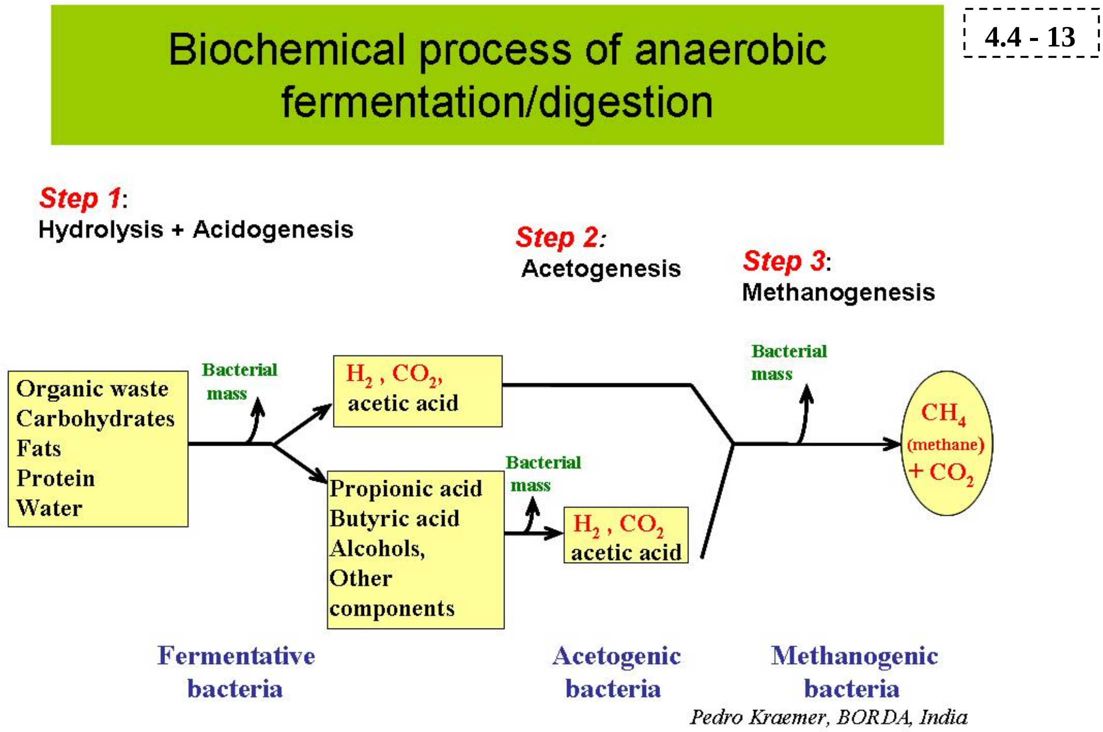
Before dealing with the chemical processes in the biogas digester, we present the more familiar processes in a landfill. The content is dominated by organic matter that is degraded over long periods according to the redox-sequence (see 4.6-19???). In a landfill with organic matter, all the processes in the aerobic-anaerobic "ladder" take place simultaneously but in different parts of the landfill. The initial oxygen in the waste is consumed soon after it is dumped (see O_2 in picture) and more and more reducing conditions develop in the deposited organic matter. Eventually, we reach the bottom step of the ladder in an environment where methane-producing organisms are favoured. A similar sequence of redox reactions can also be observed as we move down through sediments of treatment wetlands or ponds, or even in septic tanks, with methane production occurring a bit below the sediment surface.

When the waste is fresh, oxygen in the pores is consumed by bacteria that degrade the organic matter. The organic matter is quite reactive and the oxygen is fast consumed, within days (blue curve).

In the absence of oxygen, anaerobic respiration is started by either facultative or obligate anaerobs. First, nitrate is used as an oxidant (green curve) and is depleted within weeks. Further on in the process manganese oxides and ferric oxides are used. These oxides can be present in the waste itself but also in soil used to cover the waste. The next step is sulphate reduction (brown curve) and finally methane fermentation.

The redox sequence has a practical implication as the first steps produce high concentrations of total organic matter (TOC) in the leachate which consumes oxygen in water courses receiving the effluents from the waste deposit.

The methane step produces a leachate with lower TOC and in addition, for a period of about ten years it produces methane which can be used commercially as a fuel. Thus the deposition of waste involves compaction of the waste to squeeze out air/oxygen from the waste, usually by using a bulldozers and covering "pillows" of waste very soon with soil in order to reach the methane stage sooner.



The biochemical processes in a biogas digester are driven by various specialized anaerobic microorganisms. These organisms are born, work as chemical engineers, multiply and die. The bacteria have a density just over that of water, and most of them form a sludge layer at the bottom of the digester. But if the material is not properly mixed or if the Upstream Anaerobic Sludge Blanket (UASB) technique is used the sludge does not settle. Most often scum occurs due to poor mixing and it consists of sterols and fat floating up to the surface with the help of gas bubbles.

Organic matter is anaerobically broken down in a sequence of processes called the anaerobic food chain. It is divided in three phases: hydrolysis/acidogenesis, acetogenesis and methanogenesis. In the first phase, the so-called fermentative bacteria attack organic waste such as carbohydrates, fats and proteins and degrade them to simpler organic compounds (hydrolysis) and then into simple monomers such as sugars from carbohydrates, aminoacids from proteins and long chain fatty acids and glycerol from fat. These monomers are then further metabolised to alcohols ($C_6H_{12}O_6 \rightarrow 2\ CO_2 + CH_3CH_2OH$ (ethanol)) and volatile organic acids such as butyric and propionic acid and lactic acid ($C_6H_{12}O_6 \rightarrow 2\ CH_3CHOHCOOH$). In addition, acetic acid ($C_6H_{12}O_6 \rightarrow 3\ CH_3COOH + H_2$), hydrogen and carbon dioxide may be formed in various amounts.

In the second step, the alcohols and volatile fatty acids can be further digested to hydrogen and acetic acid ($3\ CH_3COOH + H_2$) by highly specialised acetogenic microbes. The biogas process is completed in the third step where a population of methanogens called *archea* (are not bacteria) utilises hydrogen and carbon dioxide to form methane ($4\ H_{2+}\ CO_2 \rightarrow CH_4 + 2\ H_2O$) and lastly a second, completely different methanogenic population of strictly anaerobic sulfate-reducing and methane-forming bacteria cleaves acetic acid to methane and carbon dioxide ($CH_3COOH + H_2SO_4 \rightarrow 2\ CO_2 + 2\ H_2O + H_2S$ and $CH_3COOH + 4\ H_2 \rightarrow 2\ CH_4 + 2\ H_2O$).

In a cow only the first step (hydrolysis and acidogenesis) occurs and part of the third step (hydrogenotrophic methanogenesis) since all volatile fatty acids are absorbed by the cow. The cow more or less lacks the step of methane formation from acetic acid. However, in the biogas digester the reactions are pushed towards complete conversion of the acids to biogas and thus it is vital that the hydrogen concentration remains high enough. In the first step (hydrolysis and acidogenesis) some of the biochemical reactions can generate hydrogen at concentrations up to 50 %. However, in the acetogenic step, other biochemical reactions are involved during the formation of acetic acid and hydrogen and they can for thermodynamic reasons only be performed at hydrogen concentrations below 0.01%. Basically the high concentration of hydrogen formed in the acidogenic step is thus inhibiting acetogenisis. Fortunately, by consuming hydrogen to low concentrations, hydrogenotrophic methanogens “push” the acetic acid generating reactions to become thermodynamically possible.

The importance of hydrogen and its effects upon the whole biogas process cannot be stressed enough. The first thing that almost always happens when something goes wrong in a digester is that the level of hydrogen increases and this limits or hinders the metabolisation of fatty acids. A biogas process that for some reasons is getting out of balance is characterised by increased levels of fatty acids.

How added organic matter to a digester affects the efficiency of digestion varies quite a lot and for many reasons. Major factors are: the amount of microorganisms that colonise the substrate, substrate quality, particle size, lignin content and retention time. An illustration of the required large amount of microorganisms is that a cellulose fibre is about 3–4 mm long and a microbe is 0.003 mm long. To a microbe, eating a cellulose fibre is like chewing on a 1 km size sandwich. Therefore, huge numbers of microbes are required on the same piece of substrate in order to manage proper digestion.

A cow chews its grass feed several times. Similarly, in a biogas digester, mechanical pre-treatment enhances the digestion rate and the degree of digestion. Another important factor is the content of lignin in the organic material. Lignin can be found in almost all types of plants to various degrees and is resistant to anaerobic digestion. Thus, a high content of lignin, such as the amounts found in wood (25–35%) makes the otherwise degradable cellulose and hemi-cellulose unavailable for digestion. Wheat straw also contains concentrations of lignin (about 10–15%) which decrease the digestibility of the straw to about 50%. Therefore, proper mixing with a focus on blending in the substrate into digester liquid is very important. Another major factor affecting digestion efficiency is the average time in the digester – the retention time. Generally a longer retention time increases digestion efficiency. While the process can in theory reduce all organic matter, this would take too long. For economic reasons, most digesters run so long that only some 40–60 % of the organic substrate is degraded. When there is no fast degradable biomass left the substrate is said to have stabilized and is less odorous.

It is important to remember that the symptom indicating that the biogas process is being impaired by toxins is exactly the same as nutrition deficiency – an increase in fatty acid levels and foaming. Such an effect can also be found in cows and this disturbance is called acidosis.

A biogas digester is not meant to hygienise organic matter. Therefore, extra efforts must be made to hygienise the slurry and sludge (see Greywater modules 4.6 and 4.7).

Pedro Kraemer, Borda-India and J-O Drangert & J. Ejlertsson, Linköping University, Sweden,

What parameters affect anaerobic digestion?

4.4 - 14

The most important determinants of good living conditions for anaerobic bacteria and therefore efficient gas production, are :

- Temperature
- Retention Time
- pH-level
- Carbon/Nitrogen ratio (C/N ratio)
- Proportion of dry matter in substrate = suitable viscosity
- Agitation (mixing) of the substrate

If any one of these determinants is outside acceptable range, the digestion may be inhibited

Pedro Kraemer, BORDA, India

We mentioned earlier that the cow's stomachs provide a stable temperature, enough water and an oxygen-free environment for efficient digestion. Any chemical process is affected by the pH-level and anaerobic digestion of biomass is no different. Also, knowing the weakness of a person with diarrhoea makes it plausible that regular feeding and long retention time is important. Less obvious is the importance of the carbon-nitrogen ratio, and we will come back to that issue.

The viscosity of the feeding material is also important. To allow easy flow through the digester, the dry matter content should be around 10%. Studies also show that feedstock particle diameter is important and that the rate of methane gas production is inversely proportional to the diameter (Kayhannian and Hardy, 1994). All organic waste such as garden waste should therefore be chopped into small pieces in order to facilitate the operation of the microorganisms.

Mixing of the substrate in the digester improves digestion, if only because it ensures a uniform material which becomes accessible to the bacteria. The cow manages this mixing by moving around and by transferring the material from one stomach to the next.

We now investigate each of the above parameters, and also identify potential inhibitors.

Substrate temperature in the digester

4.4 - 15

Anaerobic fermentation can work in an ambient temperature between 3°C and 70°C and, if colder, the reactor has to be insulated and/or heated.

Common temperature ranges for bacteria:

• Psychrophillic bacteria	below 20°C
• Mesophillic bacteria	20 – 40°C
• Thermophillic bacteria	above 40°C

Methane production is **very sensitive to changes in temperature**

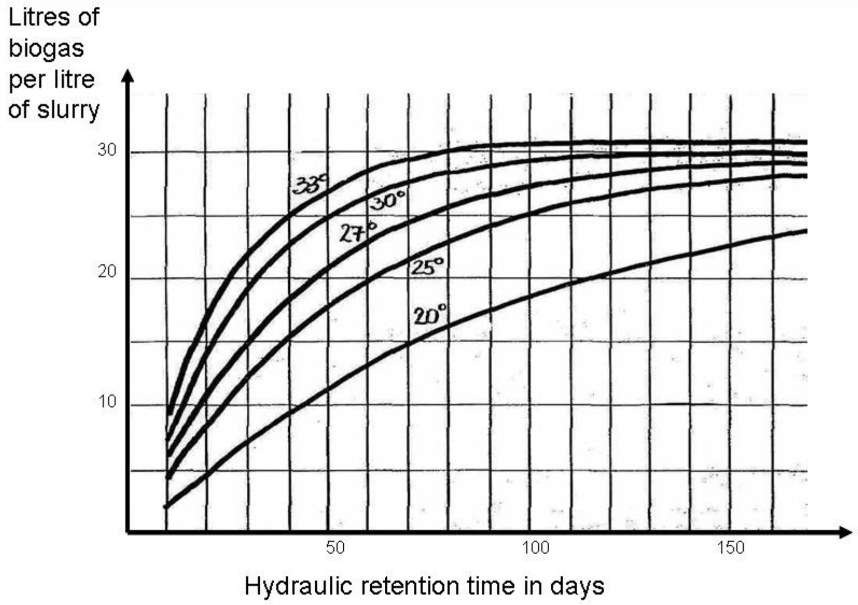
Pedro Kraemer, BORDA, India

The temperature in the cow's rumen is stable at around $37^\circ C$ and therefore mainly mesophillic microorganisms are peacefully at work. It is interesting to note that different species of microorganisms are present in the three temperature ranges, and they can only survive in their specified range (see picture above). If the temperature goes above 40^o C the mesophillic bacteria will die and be replaced by thermophillic microorganisms. If it goes below 20^o C the mesophillic bacteria will die and be replaced by psychrophyllic bacteria. However, breeding of the new bacteria population takes time and the digestion will slow down for a period.

If the ambient temperature is below $3^\circ C$, the digester should be insulated. Also, if the day and night temperatures differ much, insulation is highly recommended. The small rural biogas plants in China (see slide 4.4-7) are dug into the ground and are insulated by the soil. This is an example of how operation can be simplified and secured by a good design.

Biogas production with continuous feeding

4.4 - 16



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One kilogram of fully degraded carbohydrates gives 415 litres of methane independently of temperature (asymptotic end). The time it takes could however be affected by temperature since the rate of fermentation and biogas formation increases with temperature.

The diagram above shows how the gas production varies with mesophillic temperatures and retention time. In this case the biogas plant is fed with cattle manure mixed with some water, so that dry matter content is about 10%.

A litre of slurry can provide some 30 litres of gas (graph) in this temperature range after an extended retention time. This amount can be compared with 0.1 kg of carbohydrate giving 41.5 litres of gas (10% dry matter). The graph provides the interesting information that if the substrate temperature is raised a little, say, from 25 °C to 30 °C, the gas production in a period of 50 days goes up 50% from 17 to 25 litres. Also, the same gas production can be attained in 25 days instead of 50 days if the substrate temperature is raised 5 degrees. This, again, confirms that insulation and even heating can be very economical measures since retention times and also the size of the digester can be reduced. The cost of building a big digester is considerable, and typically it is only practical to degrade 40–60 per cent of the organic matter.

The curves may change considerably with addition of urine (+) or lignin (-) to the substrate. The reason is that urine contains large quantities of nutrients that are easily available for the microorganisms, while lignin is not degradable. Lignin´s resistance to anaerobic digestion can be exemplified by brown coal (also called ligno coal) which is made up of remains of non-putrified lignin. Another example is the build-up of organic matter as lignin in peat bogs. There are ways to increase digestion potential of the substrate including mechanical pre-treatment like chopping and limited composting before being fed to the digester.

How much is 30 litres of biogas? Household consumption of biogas may range from 600 to 2,500 litres per day depending on cooking and other habits. For instance, a lamp may use some 500 litres per day, and a 100-litre refrigerator uses 700–1,800 litres biogas per day.
A comparison with actual gas production shows that a daily addition of 20 litres of slurry is required just to run the lamp (mainly because lamps have a low efficiency shown in slide 4.4-11.

pH –value is crucial for a good result

4.4 - 17

pH is a central parameter for controlling the anaerobic process

- Optimal production when pH 7.0 – 7.2
- Inhibition (due to acids) if pH < 6.2
- Inhibition (due to ammonia) if pH > 7.6

Deviation from the optimum range results in:

- Lower gas yield
- Inferior gas quality

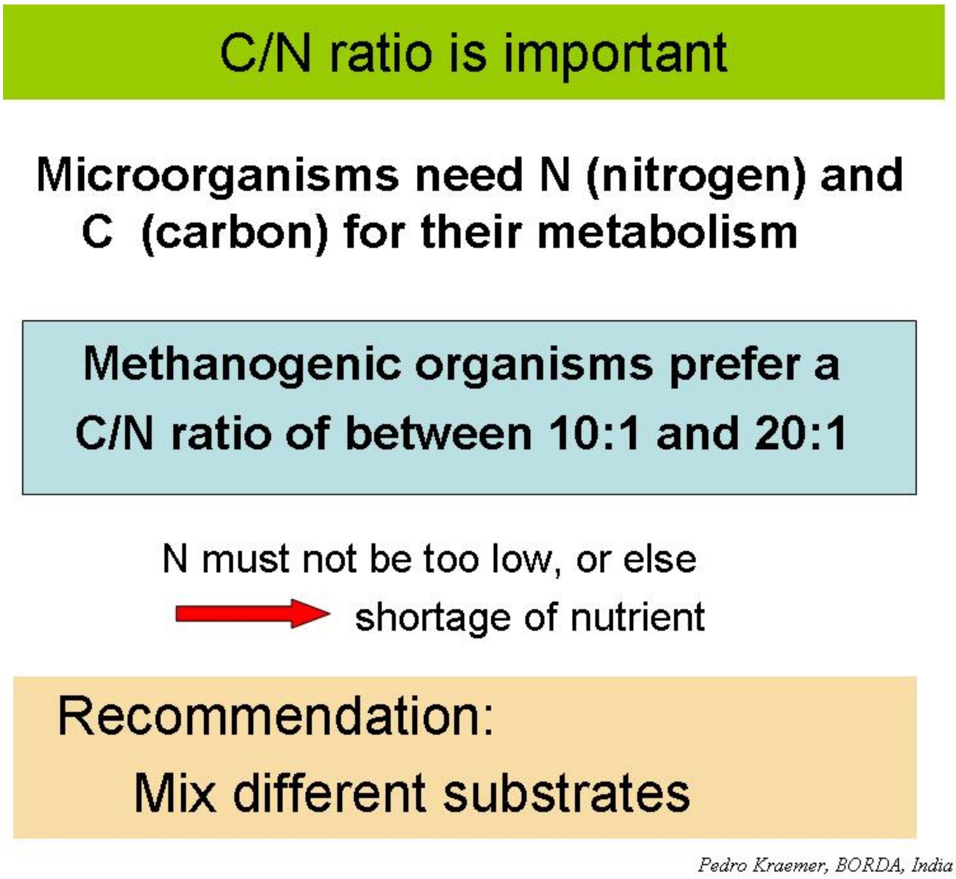
Pedro Kraemer, BORDA, India

The pH value in a digester is good indicator of the prevailing environment for the biogas processes. The pH level can change due to several reasons of which some are related to temperature and substrate composition and others to disturbances of the microbial community. Such disturbances are typically due to large temperature variations which influence the whole microbial population, or to a lack of nutrition. The acids lower the pH and if the value in the digester drops below 6.2 the acids produced by acetogenic bacteria may become inhibitory. When the environment becomes inhibitory, mainly acetogenic and methanogenic organisms slow down their reactions and finally the whole biogas process can come to a standstill.

Declining temperatures will decrease the pH of the substrate due to increased solubility of carbon dioxide in the digester liquid and sludge. Dissolved carbon dioxide is in equilibrium with carbon acid which will decrease pH. Also the composition of added substrates will influence pH: fat and carbohydrates will decrease pH during digestion whereas digestion of proteins will increase pH. Thus, a good balance between the substrates will give a suitable pH in the digester, which can be expressed as C/N ratio (see below).

The pH value can be increased by adding alkaline material such as lime or ash. If no substrate is added, the biogas production will resume and the volatile fatty acids be consumed. Adding lime water is more effective but has to be done in a way that does not increase the pH value too rapidly (Reith et al., 2005).

After the substrate has stabilized in the digester, the pH value of the slurry is commonly between 7.0 and 8.5.



4.4 - 18

Carbon and nitrogen are both vital for the digestion processes. Experience has shown that if the carbon to nitrogen ratio is too high or too low, gas production will be slower. A rule of thumb tells that a mixture of substances can achieve a convenient substrate ratio. For instance, chicken manure has a C/N ratio of 7–9 and straw has a C/N ratio of 50 to150. For further reading see Kayhanian and Hardy (1994).

The calculation of the ratio can be done for biodegradable C which is optimal for fermentation. A C/N ratio of 25–30:1 is equivalent to a C/ N ratio of 30 to 40:1 if the values are based on total C and total N (this is the conventional unit).

Nitrogen inhibition

4.4 - 19

If N concentration is too high (>1,700 mg/l of NH_4-N) and pH is high, then

→ **growth of bacteria is inhibited** due to toxicity caused by high levels of (uncharged) ammonia

Methanogens, however, are able of adapt to 5,000 - 7,000 mg/l of NH_4-N given the pre-requisite that the uncharged ammonia (NH_3 controlled by pH) level does not exceed 200-300 mg/l

Pedro Kraemer, BORDA, India

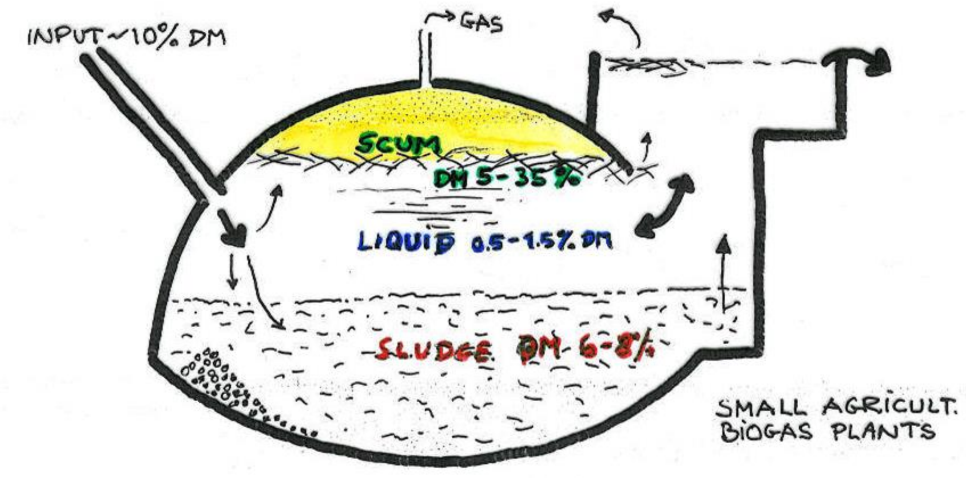
Inside the digester, nitrogen present in the substrate is released as ammonium (NH_4^+) during digestion. At pH values above 7.6 ammonium is transformed to ammonia (NH_3). If the concentration of ammonia exceeds 20–30 mg/l, the ammonia gas may be toxic to the microbial population and again biogas production will cease. High ammonia concentrations and pH values can be reduced by adding water.

Dissociation of ammonia in water depends on the temperature and pH values of the substrate: the free ammonia concentration increases with higher temperatures and with higher pH levels.

This is an example which inspired scientists to use urea as a hygienization agent for faecal pathogens (Module 4.2).

Changes in dry matter (DM) concentration inside the digester

4.4 - 20



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The recommendation for low-tech digesters is to have a viscosity or dry matter concentration of about 10% in the substrate fed to the digester. We have to strike a balance between the rate of gas production, the dry matter content and the physical operation of the digester. If dry matter is, say 15%, the gas production will increase, but such a substrate is rather solid and it can hardly flow. This leads to mechanical problems. If the dry matter content is 7% instead, the gas production will be lower but the physical operation may be easier with less mechanical problems.The 10% is important when feeding the digester. By mixing different substrates and if necessary adding some water, it is easy to reach the desired dry-matter content. Experience has shown that fresh cattle dung has 19.5 % dry matter content, human faeces 25% and human urine has 7%, while a substrate made up solely of organic waste from markets market has a dry matter content of 35–40%. A cucumber is 3% dry matter and greywater has only 0.5 % dry matter.

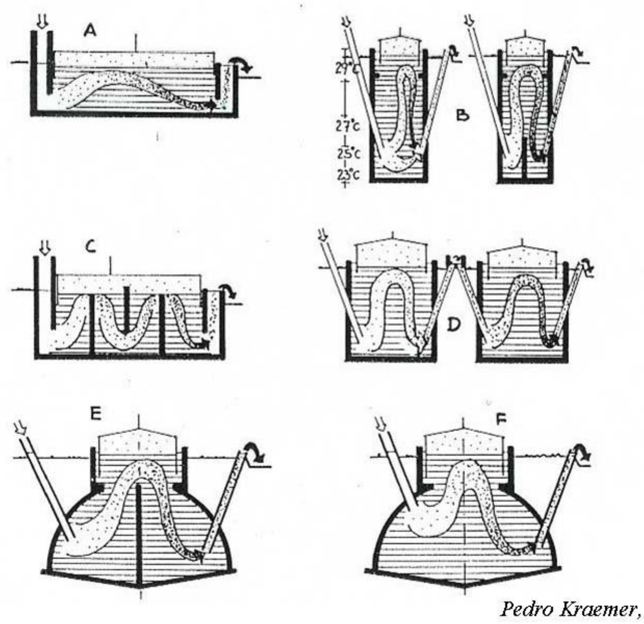
Once the feed has entered the digester the dry matter is relocated as indicated in the picture above, due to the release of biogas and other processes. The rates at which different components of the feed are digested will vary greatly. Carbohydrates in cellulose are easy to decompose (hydrolyse), but cellulose also contains 10–15% non-degradable lignin. Tree wood contains some 25% non-degradable lignin. The decomposition of proteins to methane, carbon dioxide, ammonium and hydrogensulphide is guided by pH. Fat is decomposed to biogas. What is not emitted as gases will be found in the slurry, and to a lesser extent in the sludge.

The sludge at the bottom has some 6–8 % dry matter, and the liquid slurry leaving the digester has only 0.5–1.5%. The scum layer of organic matter and dead organisms varies between 5 and 35% dry matter content and can become a hard crust.

The operator cannot observe the inside of the digester, so the only way to secure smooth operation and high gas yields is to be careful about the composition of the feed. The feed should also be shredded to ensure it does not block the movement of the substrate in the digester.

Behaviour of the substrate inside the digester

4.4 - 21



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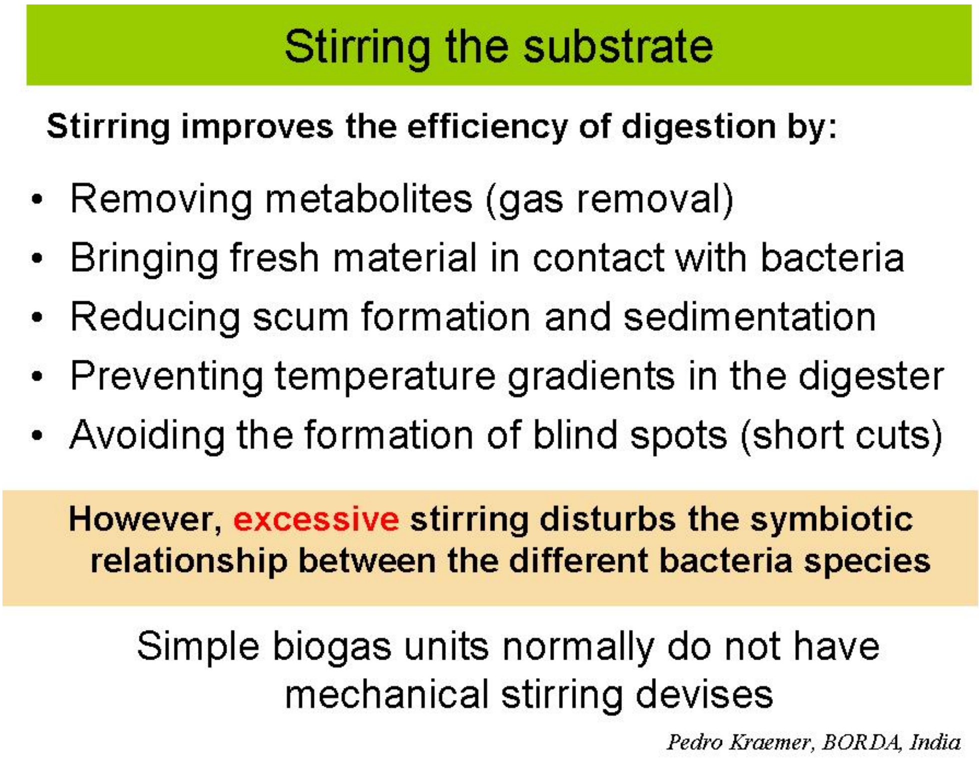
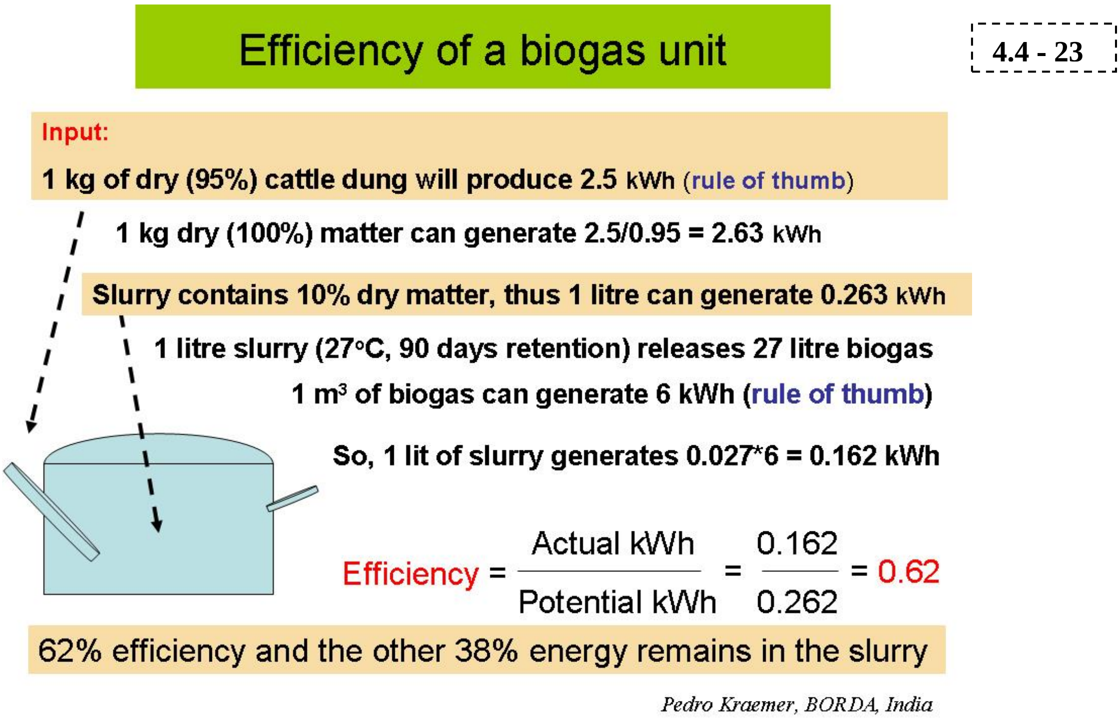
The route of the viscous substrate through the digester can be arranged in several ways, and the objective is to expose it as much as possible to the microbial population. The picture shows some of the most common designs of floating-drum digesters. The same kind of forced movement of the substrate in the reactor can be designed for fixed-dome digesters (slide 4.4-25).

During digestion the substrate will be turned into a liquid and sludge. Sludge will accumulate in the digester but there will also be continuing degradation going on in the sludge. Baffles can be inserted to make sure the substrate flows over as long a distance as possible in the digester, thereby ensuring it gets maximum exposure to bacteria. The routes shown in the pictures are all longer than a straight line and the actual retention time is longer that the theoretical one. If the retention time is one week the movement of the substrate is slow, and the bacteria have easy access to the slowly passing feed. There is no turbulence and so bacterial activity is not disrupted.



4.4 - 22

Stirring the material in the digester improves gas production for the reasons given in the slide. It can be done mechanically with a rod, or by injecting compressed biogas from the bottom of the digester. The bubbles move the substrate around and give bacteria access to all of it. However, it should be done gently to avoid disturbing the symbiotic relationships between different bacteria species.

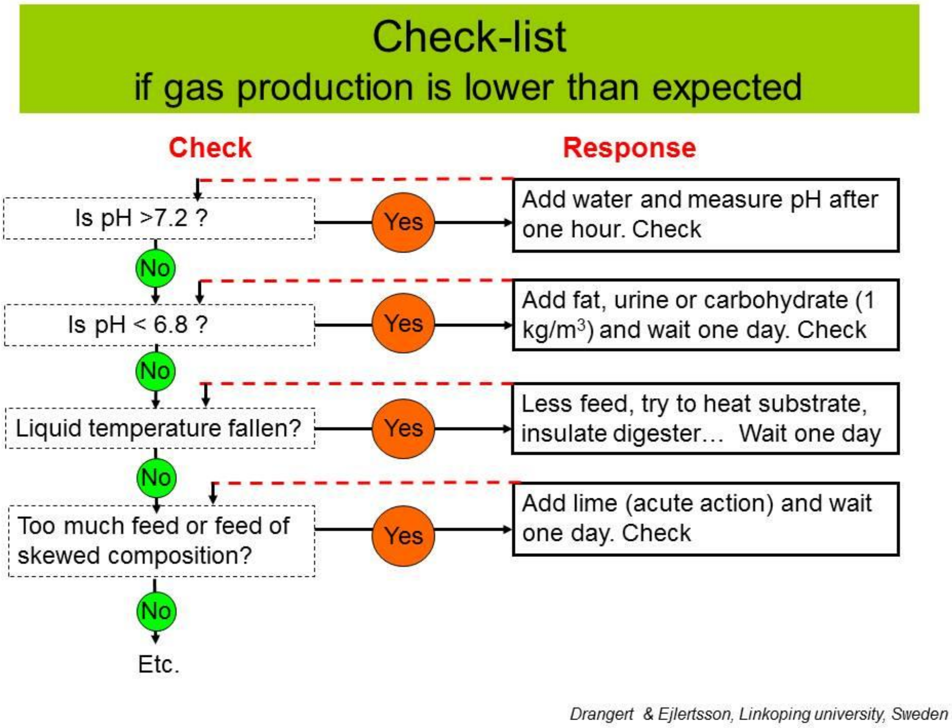


The calculations in the above slide are based on experience in the field:

1 kg of dried (95%) cattle dung releases about 2.5 kWh of energy

1 m^3 of biogas generates some 6 kWh of energy

What the calculations above tells us is that if the retention time is three months, typically about two-thirds of the potential energy is taken out of the substrate as biogas and one-third remains in the liquid leaving the digester with the slurry. However, this liquid contains nitrogen and other nutrients and can be used as a fertiliser and so it is not wasted.



4.4 - 24

If gas production is lower than expected, the parameters mentioned in 4.4-13 have to be assessed. However, some of these parameters cannot be measured easily in a household unit. Therefore the checklist is arranged so that the parameter that is the most common cause of problems, or the parameter which is easiest to check, comes first, followed by the others.

(1) ***PH-value***: The pH-value is the most critical parameter during the digestion process and cheap pH measuring sticks are available on the market. Furthermore, pH is easy to measure with a litmus test. If the pH-value exceeds 7.2 water should be added to the digester to dilute the sludge (slide 4.4-16).

A low pH-value (< 6.8) may be caused by several factors. If too much substrate is fed into the digester, methanogenic bacteria are not able to produce enough methane and acidification takes place. If the pH-value is below 6.9, no more biomass should be added until pH returns to a value of between 7 and 7.2. If the pH value falls below 6.6 there are two ways to increase pH. The first is dilution with water. The second is to add chemicals like lime water (or urine). As bacteria adapt only slowly to new conditions the chemicals must be added slowly.

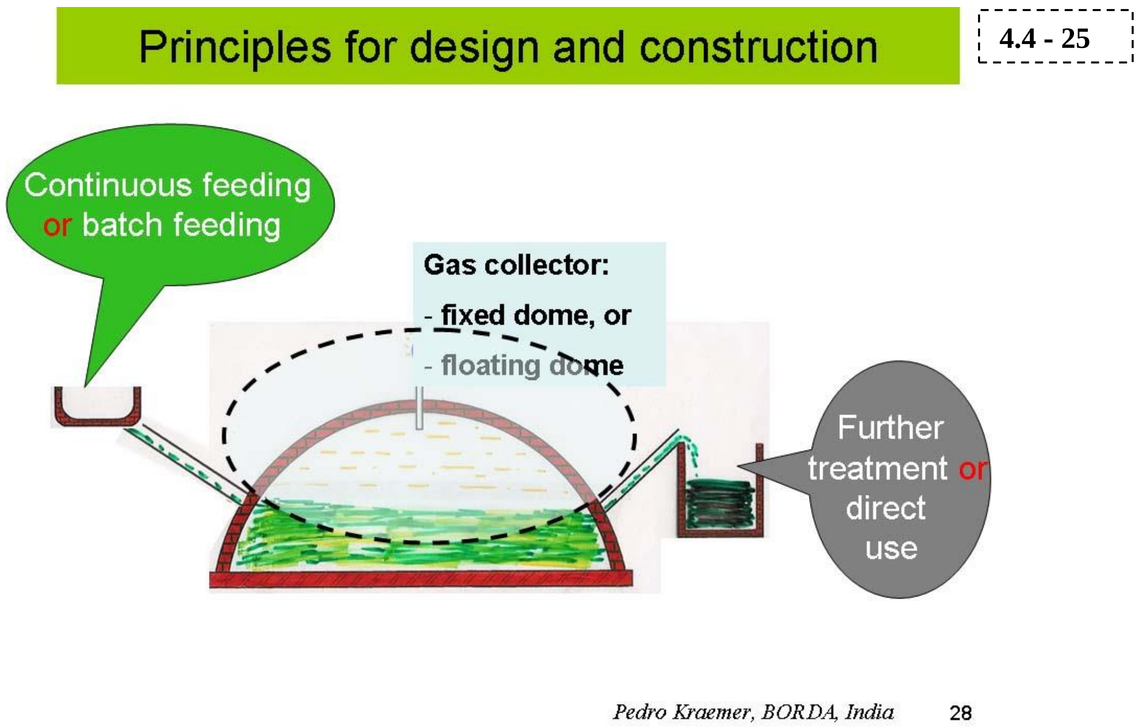
(2) ***Temperature***: Temperature affects the pH. Decreasing temperature allow more carbon dioxide to dissolve in the digester liquid. Dissolved carbon dioxide forms carbonic acid which decreases pH. Thus, low gas production may be caused by a drop in temperature which also chemically will decrease pH. A declining temperature also decreases the rate of digestion, where especially the methanogenic populations loose pace. In low-tech digesters, it is not possible to solve this problem instantly. A long-term solution is to insulate the digester and preheat influent feed. A new heating process should be started slowly (maximum 1 degree Celsius per day).

(3) ***Substrate composition***: The composition of the substrate is very important, especially for co-fermentation of various substrates (slides 4.4-17 –19). For example, chicken and swine dung are known to cause problems because both have high values of fat and carbohydrate and so they may cause acidification. Another possible problem is the concentration of sand in dung that accumulates at the bottom of the digester.

(4) ***Toxic material***: Toxic material may inhibit or even kill bacteria and other microorganisms. But it is difficult to analyse samples for toxic materials like heavy metals, medicine residues, solvents or disinfectants, because the concentrations of these toxic substances are very low. The only solution is to encourage adding of less polluted wastewater and to avoid mixing organics with other solid or liquid wastes.

(5) ***Total Solid*** (TS): If the effluent contains a rising TS volume it is possible that the digester is leaking. It is also possible that the composition of the substrate has changed and it has dry matter content above 10%.

(6) ***Agitator***: The agitator (slide 4.4-21) extends contact between degradable substances and microorganisms. Less gas production may be caused by improper performance of agitators.



Up to now, we have discussed biochemical and other processes involved in biogas production. As will be shown in this module there are certain principles guiding the design and construction of well-performing digesters.

A digester chamber must not have any leakage points where water can seep into the ground or gas escape into the air. If made of bricks and cement the workmanship has to be meticulous. There should be a manhole big enough to enable a person to enter the digester for repairs.

There are essentially two basic approaches to producing gas. One is the biogas digester that uses lots of organic waste as substrate and produces large amount of biogas, while at the same time reducing the problem of waste disposal. The other approach is to collect gas from the wastewater treatment process, despite its low organic load. In this case the volume of gas is moderate, but the reason for collecting it is to avoid the release of greenhouse gases.

Biogas digesters:

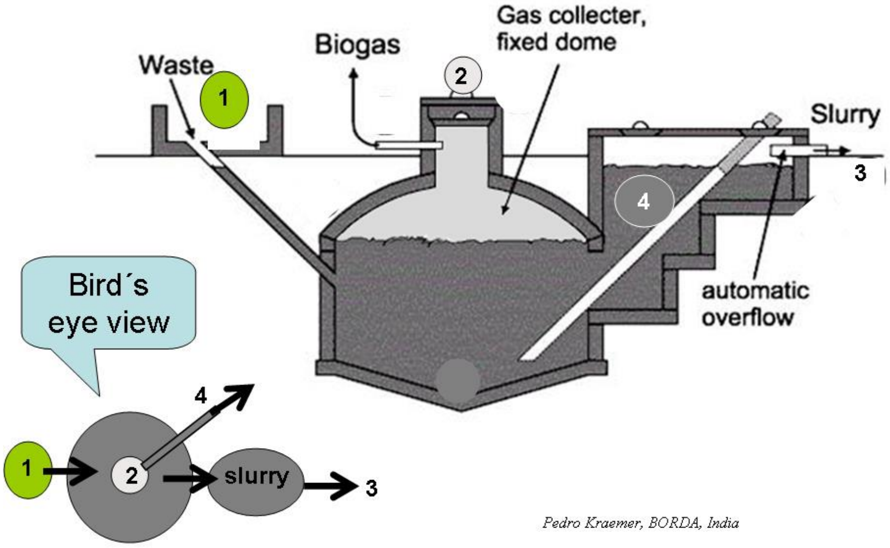
There are different ways of feeding the digester. Continuous feeding is the most commonly used. There should be enough space to store the organic material and to mix it before feeding it into the fixed-dome digester or floating-drum digester. It is recommended that the inlet to the digester has a shape that makes it possible to judge by eye inspection the volumes of added feed and water. Also, the inlet should be such that it is easy to read the height of the material standing in the inlet pipe in order to take a pH test, and to measure the temperature of the substrate in the digester.

Anaerobic (baffled) reactors

The degradation of organic material in wastewater treatment plants produces some biogas that can be collected. The purpose is not to produce biogas, but it is a by-product of most anaerobic treatments. Module 4.7 provides examples of wastewater treatment plants, for instance in anaerobic filters or the Upstream Anaerobic Sludge Blanket (UASB) digester (slides 4.7-8--10). The tunnel digester is an example of a plug-flow digester which is more or less a tube the wastewater has to pass through.

Fixed-dome biogas digester

4.4 - 26



There are several designs of biogas plants, and we first show the Chinese invention of a fixed-dome digester. Its advantages are low initial cost, simple operation since the scum layer breaks automatically, and low maintenance. There are no moving or rusting parts so it has a long life. The movement of the substrate relies on hydraulic pressure from the added feed. The downside is fluctuating gas pressure. Furthermore, qualified and experienced masons are required to build the gas-tight fixed-dome digester.

Organic solid waste including manure and faeces are mixed with wastewater to a watery mass with 10% dry matter content (No 1 in picture). This is fed to the digester where anaerobic micro-organisms decompose starch and other materials to methane gas and other products (see slide 4.4–13).

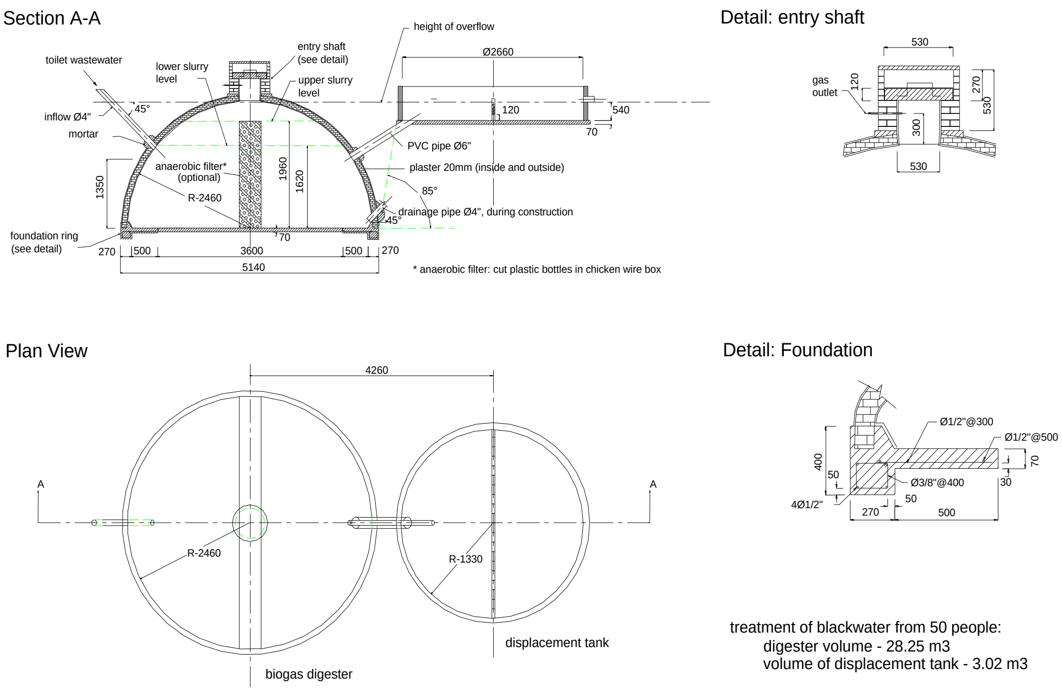
The gas rises through the scum layer to the upper part of the fixed dome. As pressure builds up, the liquid in the digester is pushed down and will escape as slurry (No 3). If the gas is not let out (No 2) it will start seeping out in the slurry chamber, because this exit is the first available when the substrate level sinks. So, it is easy to know from the smell when to empty the gas. When gas is let out (No 2) the liquid substrate rises again and the crusty scum layer on top breaks into pieces since the diameter of the dome is ever smaller. This makes the system very robust and there is no need to enter the reactor or use a mechanical device to crack the scum crust.

The white pipe (No 4) is used for emptying the degraded material (sludge) at the bottom of the reactor. It is not inserted through the slurry opening as it may appear in the diagram; it enters from another direction as shown in the bird's eye view. The slurry (No 3) is still rich in nutrients (except N) and other compounds that have not been decomposed. Therefore, it is suitable as fertiliser. The digester is not meant for reduction of pathogens, but there is a 1–2 log unit reduction of bacteria.

4.4 - 27

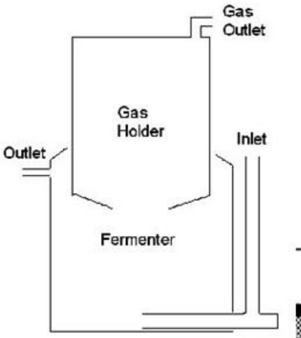
The pictures show the construction of fixed-dome digesters in different Latin American countries. The circular-shaped brick wall (top-left from Cuba) is built on a cement fundament. The dome is built with bricks and cement and a skilful mason does not need a support under the dome (top-right). After the cement has hardened it is possible to add the manhole (bottom-left) and gas pipe on top of the dome. The inside of the dome, the wall and floor are “painted” with water-proof cement 3–4 times in order to ensure that it is airtight (bottom-right).

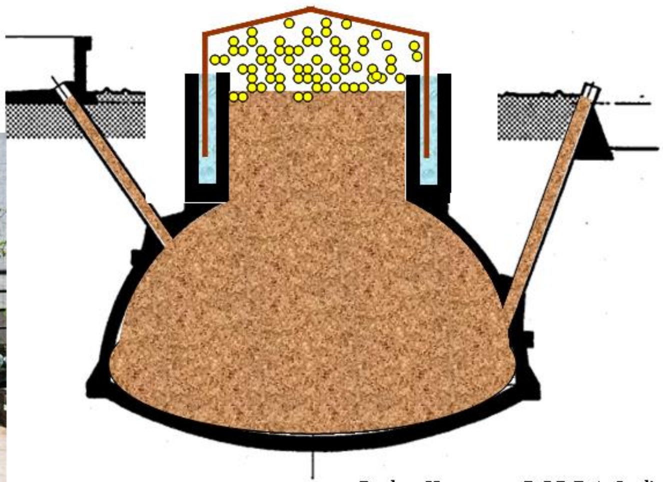
Biogas digester



Floating-drum unit with water-jacket

4.4 - 28





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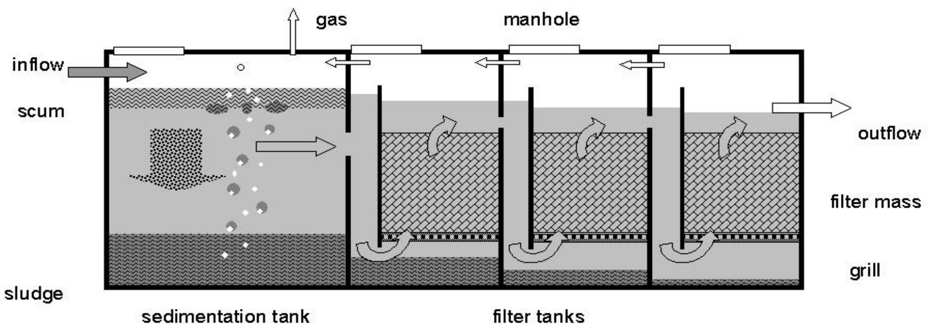
Another design is the floating drum. The reactor can be above ground (left) or in the ground (right). The top of the digester is made airtight by keeping the upside-down drum dipped in a water apron (right-hand picture). The drum is pushed upwards by the gas, while the substrate level is pushed down to a small extent by the weight of the drum. The position of the drum shows when it is time to empty the gas. The gas pressure is even and can be adjusted by selecting the weight of the drum. This is an advantage since gas lamps and gas burners work more efficiently with a constant high gas pressure.

This design requires the same kind of operation as the fixed-dome digester, except that it may be necessary to crack the scum layer by lifting off the drum. The downside is that the drum is relatively expensive and requires a lot of maintenance.

The small single-household unit (bottom left) is made of plastic and works on the same principle. The unit can be placed in the corner of the garden or on a roof garden. It is sensitive to changes in temperature and should be insulated if day- and night temperature differs much.

Anaerobic filter (off-plot system)

4.4 – 29



Pedro Kraemer, BORDA, India

Anaerobic filters are used as part of a wastewater treatment system in order to catch the gas released in the processes. The influent has a low content of dry matter (about 1%), which is very different from biogas digesters which contain 10 % dry matter.

The anaerobic filter, also known as a fixed-bed reactor, comprises a fixed bed of tanks and the wastewater flows through a sequence of filters made of gravel, slag or plastic elements. The wastewater flows continuously and both upstream and downstream flow through the filters are design possibilities. The wastewater is pre-treated in a sedimentation tank to prevent clogging.

Gas is produced in all tanks and collected in a gas storage tank. All the tanks have to be airtight to prevent the gas from escaping. Anaerobic organisms are added to improve degradation of organic matter in the wastewater.

Microorganisms grow on the filter material and make up a so called biofilm. The smaller the pores, the larger is the contact area of microorganisms and wastewater. The downside is that smaller pores may clog or even block totally, so there has to be a balance between pore size and contact area. Clogging means that dissolved and non-settleable solids adhere to the filter material or simply physically block passageways and in both cases they diminish the permeability of the filter. The few small channels still open to water flow compel a high-speed flow which washes away the bacteria. Also, high local speed provides little time for the bacteria to work and poor effluent quality can be observed. Back-flushing of the anaerobic filter has to be done regularly to prevent such operational problems. If operated correctly, the anaerobic filter is reliable and robust.

One anaerobic filter can serve many households, and take care of wastewater from institutions and public conveniences.

Another biogas technology to capture gas from wastewater is one without filters. The Upstream Anaerobic Sludge Blanket (UASB) reactor contains in this case an active sludge blanket at the bottom of the reactor (See slide 4.7–10). The reactor is designed as an upstream system with the inlet pipe at the bottom of the chamber. Instead of forcing the wastewater through a filter, the upstream flow gently pushes the sludge upwards in the reactor, but it remains in the lower strata of the reactor. Here, the microorganisms attached to sludge particles attack the substances in the surrounding wastewater. This is what is meant by “activated sludge”.

4.4 -30

The Anaerobic Baffled Reactor is a combination of a UASB reactor with the principle of a septic tank. This is a technology often used for housing complexes and institutions such as hospitals and schools.

The larger solids in the wastewater settle in the first sedimentation (septic) tank followed by a sequence of connected chambers. Each inlet to a chamber is at the bottom so that the flow of wastewater disturbs the sludge and it whirls up in the water body. Each outlet is at the top, forcing the wastewater to flow upwards and the sludge particles try to settle because of weight. The microorganisms attached to the sludge particles are exposed to the surrounding wastewater and start degrading organics and other solids. The advantage gained is good wastewater exposure to the microorganisms. The drawing shows that the chambers receive less and less settled sludge (slide 4.4-29).

This treatment system is very robust against hydraulic and organic shock loads, and easy to operate. Unlike the UASB, there is no risk of clogging. Even difficult-to-degrade solids are affected, thanks to the very long retention obtained in the settled sludge. Such solids are hydrolysed and fermented by acidogens so that they after some time are transformed into biogas.

Biogas is produced in all the chambers and collected in a storage tank. The construction must therefore be air-tight in order not to lose any gas. The gas pressure fluctuates and is therefore not ideal for household appliances.

Some design data are given in the table and sketch below:

General Spread Sheet for Baffled Reactor with Integrated Settling Tank

daily waste water flow	time of most waste water flow	max peak flow per hour	COD inflow	COD / BOD ratio inflow	Settleable SS / COD ratio	lowest digester temp.	de-sludging interval	HRT in settler	BOD removal rate in settler	COD removal rate in settler	inflow into baffled reactor		org. load limit factor
avg.	given	max.	given	given	given	given	chosen	chosen	calcul.	calcul.	BOD	COD	calcul.
m³/day	h	m³/h	mg/l	mg/l	mg/l / mg/l	°C	months	h	%	%	mg/l	mg/l	factor
610	**12**	18,00	**1.540**	**1,47**	**0,30**	**30**	**12**	**1,50**	17%	16%	874	1.296	1,00
usual values =>			*domestic*	*1,7-2,0*	*0,5*			*1,5 h*	TIP:set HRT=0 if no settler provided				

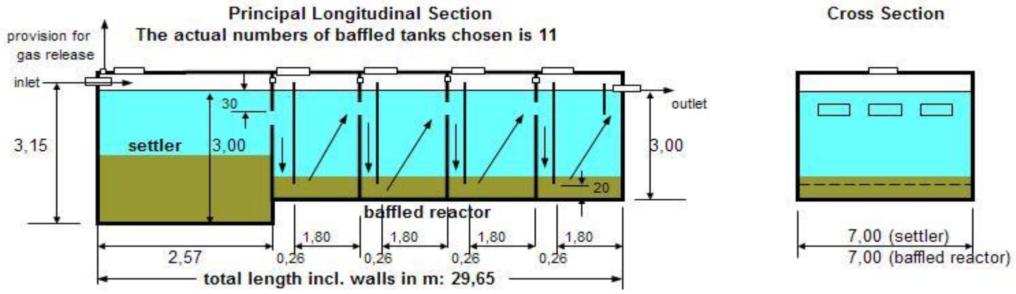
Data for Calculation of Baffled Reactor / **Dimensions Settler**

factors to calculate BOD removal rate of baffled reactor		BOD rem. 25°, COD 1500	theor. rem rate acc. to factors	BOD rem.rate baffle only	COD rem.rate baffle only	BOD out	COD out	total BOD rem.rate	total COD rem.rate	inner masonry measurements chosen acc. to required volume		length of settler	length of settler
calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	calcul.	width	depth	calcul.	chosen
f-strength	f-temp	f-HRT	%	%	%	mg/l	mg/l	%	%	m	m	m³	m
0,98	1,10	92%	99%	98%	97%	17	38	99%	98%	**7,00**	**3,00**	2,57	**2,57**
										sludge l/g BODrem.		*0,0027*	

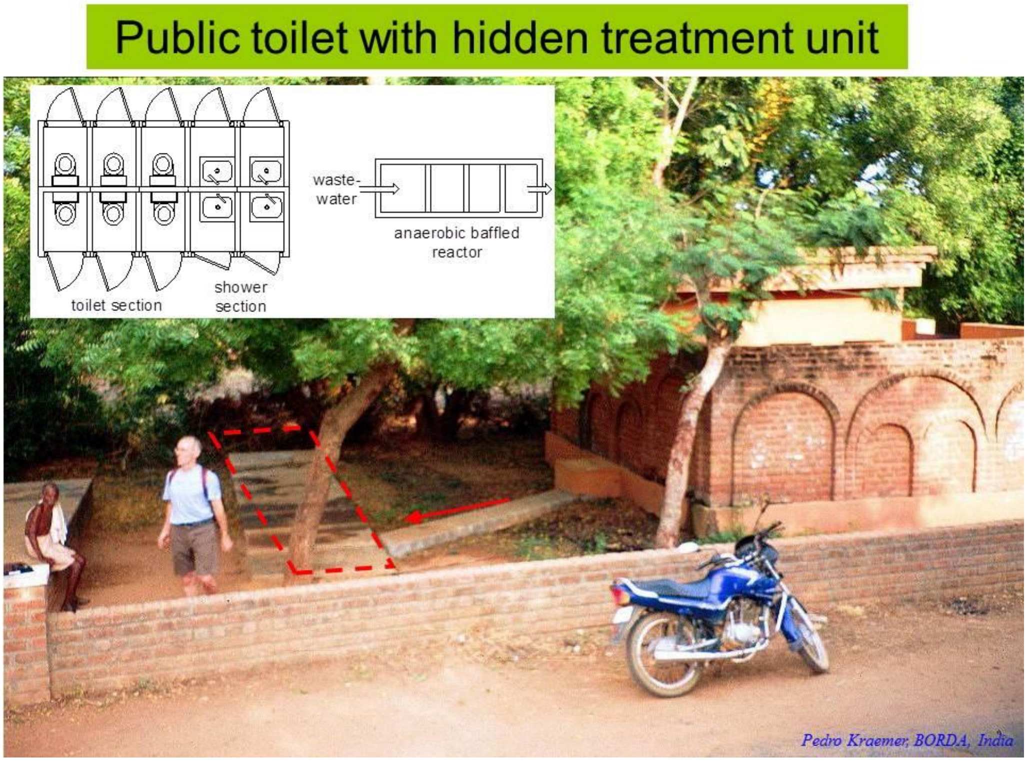
Dimensions Baffled Reactor

max upflow velocity	number of upflow chambers	depth at outlet	length of chambers *should not exceed half depth*		area of single upflow chamber	width of chambers		actual upflow velocity	width of downflow shaft	actual volume of baffled reactor	actual total HRT	org. load (BOD)	biogas (ass: CH_4 70%; 50% dissolved)
chosen	chosen	chosen	calcul.	chosen	calcul.	calcul.	chosen	calcul.	chosen	calcul.	calcul.	calcul.	calcul.
m/h	No.	m	m	m	m²	m	m	m/h	m	m³	h	kg/m³*d	m³/d
1,65	**11**	**3,00**	1,50	**1,80**	10,91	6,06	**7,00**	1,43	**0,26**	475,86	18	0,79	157,10
1,4m/h; max<2.0 m/h										*HRT reduced by 5% for sludge*			

TIP: If removal rate is insufficient; increase number of upflow chambers. Then, HRT will increase also but upflow velocity remains low.



4.4 - 31

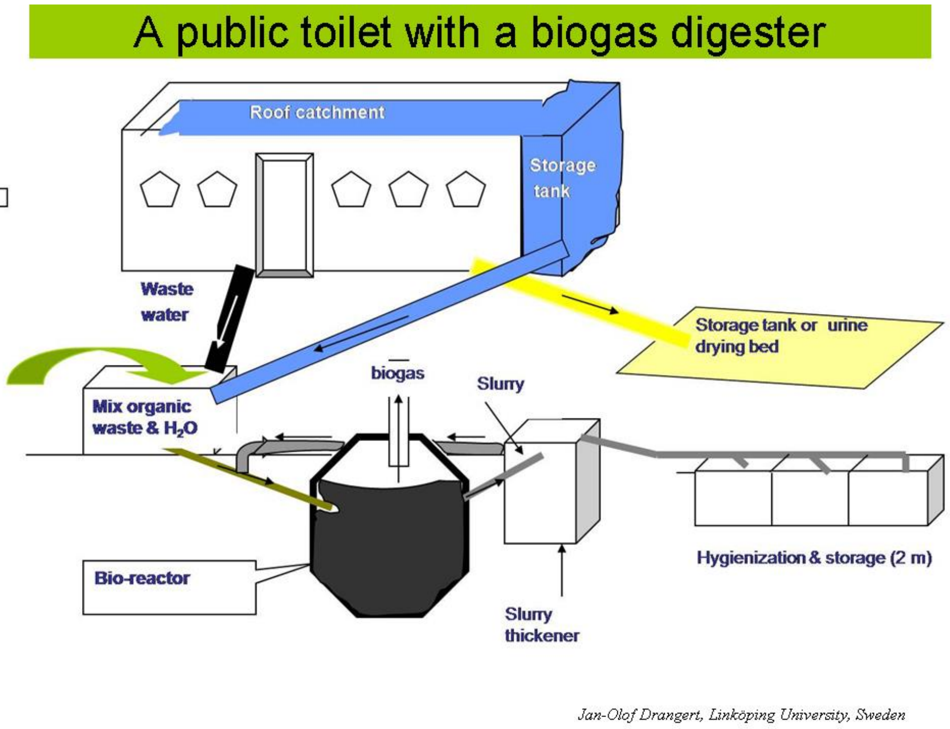


A practical example of an anaerobic baffled reactor is shown in the picture above. This DEcentralized WAstewater Treatment Systems (DEWATS) receives wastewater from a public toilet to the right. The digester is “hidden” in the ground (indicated) and does not require any extra space. It can therefore be readily integrated into public areas like parking lots, parks, foot paths etc. As mentioned earlier, the reactor is tolerant of peak loads and fluctuations in flow. The unit is easy to operate, and a trained gardener can take care of its maintenance including calling a vacuum truck for desludging.

The sludge in the chambers is removed and after some composting becomes safe and good manure since very few chemicals have been added in the public toilet – ideally only biodegradable substances which contains very few chemicals. It is safer to dispose hormones on soil than in water bodies (see Module 3). The biogas is collected in a gas tank from which the gas can be used for lighting, heating or cooking.

The treated effluent is clear but not safe water, and will need some treatment depending on subsequent use. This effluent water is good for irrigation and fertilisation, despite about half of the organic matter has been converted and removed.

The ABR can be built with local materials by a contractor with skilled masons. The capital cost is moderate and can be estimated by any contractor. A design proposal is shown in 4.4–30.

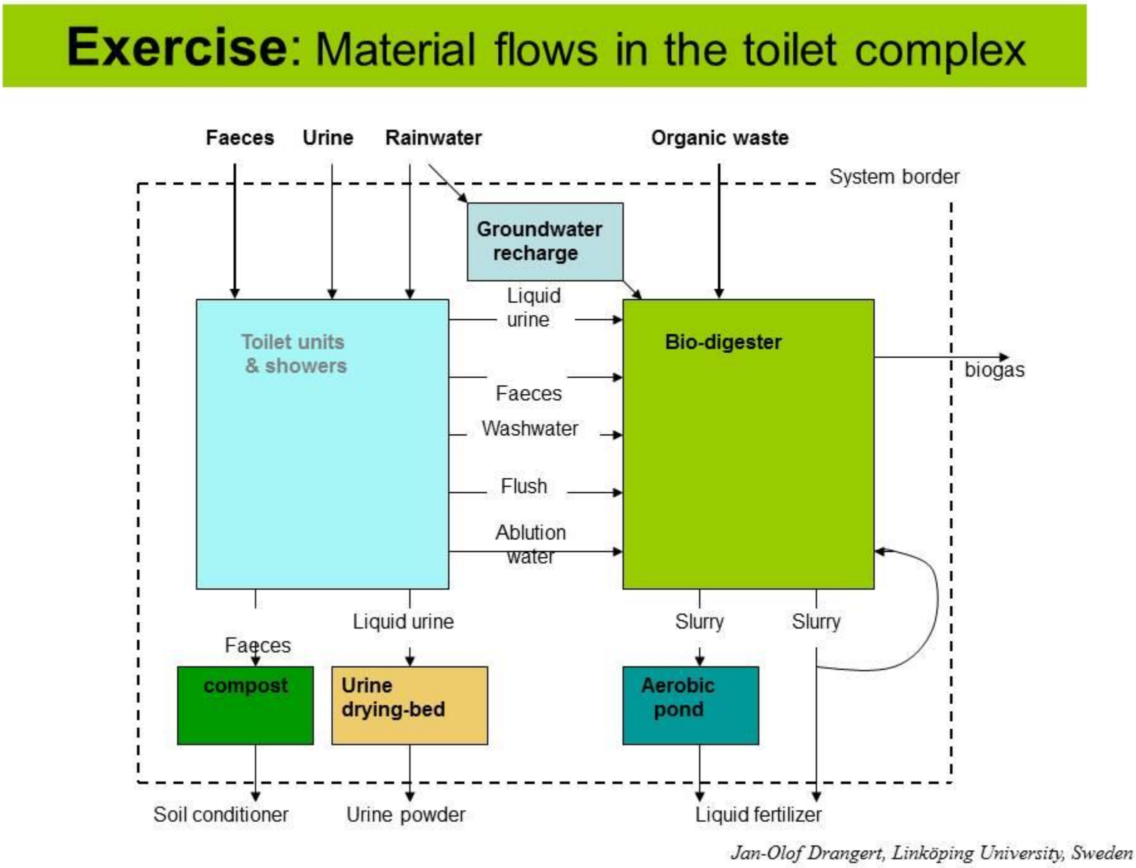


4.4 - 32

This picture shows a public toilet system connected with a bio-digester in an urban area with no access to tap water or sewerage. The municipality may have built this public toilet adjacent to a market to solve the dual problems of providing a public toilet service and collection of organic market waste.

Rainwater is collected and during dry season well water is drawn. The water is used for handwashing and to flush pour-flush toilets. Minimal water volumes are required since the inclination of the pipe to the nearby digester is steep. The digester is designed to degrade all the market waste and to treat the wastewater from a public toilet. Urine is diverted and used directly as a fertiliser in agriculture. The remaining toilet water and greywater is treated in the digester. Afterwards the slurry is hygienised and applied in a nearby garden or used to feed the digester.

A calculation exercise follows on the next slide.



This is a schematic picture of the material flow in the public toilet complex and incoming organic waste from the market described in slide 4.4–32. It can be used as an exercise to find out what can be produced from the potential waste. The input data has to be gathered from the field or be invented for this purpose.

The material flow concept was introduced in Module 1.3 and can be applied here. The rules of thumb for equations, sinks and flows are found in the previous descriptions of bioreactors. A rough first calculation can be done manually, while a scenario or sensitivity analysis will require a mathematical model with an associated computer programme.

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