Technology review of biogas sanitation

Draft - Biogas sanitation for blackwater, brown water, or for excreta treatment and reuse in developing countries

giz
Sustainable sanitation
ecosan

On behalf of
Federal Ministry
for Economic Cooperation
and Development

Imprint

Published by:
Deutsche Gesellschaft für
Internationale Zusammenarbeit (GIZ) GmbH
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Place and date of publication:
Eschborn, July 2010

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Cover: © Florian Klingel, Nadira Khawaja,
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Back: © Christian Rieck, Nadira Khawaja,
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1 Summary

Anaerobic treatment units as part of an on-site decentralised or semi-decentralised wastewater treatment system are an alternative to centralised wastewater treatment systems due to their energy and soil conditioner production capacity, low-tech components and adaptability. It is also an excellent technology for organic sludge treatment, collected from septic tanks, holding tanks, dry toilets, settlers or from aerobic wastewater treatment systems.

The main advantages of the anaerobic treatment process compared to the aerobic treatment process are the generation of biogas and significantly less sludge production. The fact that the plant nutrients phosphorus and pottasium are not removed in the treatment process can also be an advantage for the application of the effluent in agriculture to replace chemical fertiliser; the effluent should never be discharged directly into water bodies without further treatment, unless the carrying capacity of the receiving water body is not exceeded.

Sanitation concepts for brownwater or blackwater of faecal sludge (excreta) based on anaerobic technology have advantages in terms of nutrient recycling, energy balance and CO_2-emission reduction compared to conventional aerobic wastewater treatment systems.

The flush toilet generates a wastewater which is not suitable for on-site treatment in a small-scale biogas plant, unless animal excreta is added, as water dilutes the organic matter and requires an increment of the construction volume. Or the flush water amount has to be reduced by means of water saving toilets, or pre-settling or screening process. Toilet blackwater alone could not produce enough biogas to cover completely the energy demand for cooking or lighting of a household. The biogas yield could be increased by feeding easy biodegradable organic kitchen waste or animal dung into the digester. An organic garbage disposal unit in the kitchen sink (grinder), is useful in this respect. But in this case the design and volume of a biogas plant system should be adapted to treat higher solid content than only blackwater alone.

In decentralised or semi-centralised wastewater treatment systems, biogas sanitation units are often designed as primary treatment of wastewater to remove large particles and some organic matter by settling and digestion (Sasse, 1998).

Local circumstances must be taken into consideration, such as the amount of excreta, blackwater or brown water; the dilution of the influent with flush water or urine; addition of organic waste; the settleable solids content in the influent; the climate and soil temperatures; available space; and the intended reuse or disposal pathway.

Four types of biogas sanitation units are briefly described in this document: (a) the biogas settler (BS) or biogas septic tank (BST); (b) the anaerobic baffled reactor (ABR); (c) the anaerobic filter (AF); (d) the upflow anaerobic sludge blanket reactor (UASB).

This publication contributes to spread awareness about the anerobic technology for sanitation purposes.

2 Introduction

2.1 Target audience

To understand this document a basic technical background is needed. The target audience are interested people who:

- want to get an overview of biogas sanitation, the different designs, their application, efficiency and technical components;
- want to know the most important documents written in this field for further reading;
- have a particular interest in developing countries, especially from the perspective of households and communities with economic limitations.

2.2 Scope of this document

A sanitation system does not consist of a single technology. A complete sanitation system consists of a chain of technologies, each taking care of a specific function, such as the toilet, the transportation, the storage, the treatment, and the reuse or disposal of rcyclates. The here described treatement systems “biogas sanitation” purify a wide range of wastewater; the present publication focuses on storing and treating blackwater or brown water, excreta, faecal sludge, wastewater from low or no flush toilets and kitchen waste. Such treatment concept can easily be combined with urine diversion systems treating anaerobically only the brown water which consists of toilet flush wastewater mixed with faeces, or dry feaces, but prefferably without urine.

Hence, greywater, mixed domestic wastewater, manure form animal husbandry, and industrial wastewater treatment is outside of the scope of this document.

2.3 Definition of biogas sanitation systems

Biogas sanitation systems are defined by the authors as ‘‘engineered systems designed and constructed to utilise biological processes which break down solids and soluble organics in the liquid by anaerobic bacterial action under exclusion of free oxygen in treating organically loaded sludge, excreta or wastewater’’.

A clear differenciation between wastewater and solids treatment has to be made: for the first one, bacteria have to be accumulated and kept in the system, while in the second one solids are hydrolysed and then converted into biogas. Anaerobic wastewater treatment and biogas sanitation are using the same biological process, but the goal of anaerobic wastewater treatment is to purify wastewater, rather than to prepare it for fertilising reuse and to produce biogas. The purification is the result of the breakdown which occurs in the absence of oxygen (anaerobic conditions).

Figure 1. Construction of biogas digester at Meru prison, in Meru, Kenya – type: biogas settler, fixed dome (source: S. Blume, 2009)

The construction design of biogas sanitation units is nearly the same as for completely mixed domestic wastewater treatment but it can be smaller volumed if designed for blackwater or brownwater, excreta or faecal sludge only, depending on the way how active bacterias are retained, and the time required to degrade and sanitize the input material.

2.4 Historical development of biogas sanitation systems

There are different expressions used for the same technology: biogas sanitation system, anaerobic digestion, anaerobic fermentation. These systems have been used for excreta treatment for more than 100 years, thus improving surface water quality and sanitation in many regions of the world.

Anaerobic digestion is one of the oldest technologies applied for wastewater treatment. Louis Mouras of Vesoul, France, was given a septic tank patent in 1881 and credited with the invention. Baffles, which regulate the flow, were added in 1905 to make the septic tank more efficient. The first baffles were made of oak boards[1]. It is reported that the septic tank was first introduced in the USA in 1883, in England in 1895 (already as biogas septic tank) and in South Africa in 1898.

The first biogas septic tank unit usually referred to in the literature is the biogas sanitation unit at the Mantunga Homeless Lepers Asylum near Mumbai, India, built in 1859. Its primary function was sewage treatment, but the biogas was also used. Another sewage treatment plant designed as a biogas plant was installed in 1938 in Mumbai-Dadar (Eggerling 1985). In 1978, an experimental community sanitation biogas plant with support of UNICEF was implemented in Uttar Pradesh in India[2]. Since then community biogas sanitation systems have been promoted by various stakeholders throughout India.

In 1895, the technology concept of a biogas septic tank was developed in Exeter, England, where a septic tank was used to generate biogas for the sewer gas destructor lamp, a type of street gas lighting. Also in England, in 1904, the first dual purpose tank for both sedimentation and sludge treatment (biogas settler) was installed in Hampton.

In 1907, the German engineer Karl Imhoff designed a continuous operating two-stage sewage tank system. The system is called the Imhoff tank. In this system, the settling zone of particles is separated from the sludge digestion zone, where biogas is generated.

In China, the small-scale agricultural biogas plant was developed in Taiwan in 1920, based on urban household septic tanks (Guo-Qiang 1992). As a standard, the toilet and the pigsties were connected to the same underground digester (Crook 1979). In order to treat collected faecal sludge and excreta, the city of Qingdao started the operation of the first large scale biogas sanitation digester in July 1978. At the same time, the Zhangzhou College of Education developed a small-scale 3-step biogas digester for anaerobic treatment of excreta from household dry toilets (Yongfu et al., 1992).

A major increase in the number of pure biogas sanitation systems took place in 1984, as the application expanded with the development of the "Purifying Domestic Sewage Biogas Tank" developed by the Chinese Chengdu Biogas Research and Development Centre (Cheng and Yao-fu, 1991). Since then many public toilets have been connected to biogas septic tanks, composed by biogas settlers, anaerobic baffled reactors and anaerobic filters.

In 1980, on behalf of the Federal Ministry for Economic Cooperation (BMZ), GTZ/GATE instituted a "Biogas Extension Programme" (1980-1993) as part of German development aid. It was prompted by the realization, and by analyzing the results of the first German supported biogas projects in Nepal in 1976, in Cameroon in 1978, and short-term consulting work done between 1977 and 1980. Only proven basic designs from China and India with good building material were used. Piping was changed to galvanized steel or HDPE pipes only, instead of garden hoses and gate valves, which both leak after a short time.

The first national biogas program supported by German Development Cooperation using toilet wastewater and human excreta as feedstock, and introducing nation-wide biogas sanitation at boarding schools, build with World Bank support, was conducted under the lead of the Ministry for Energy and Mining in Burundi. The project was initiated as Biogas Dissemination Programme in 1984 in the region of Cankuzo; it became part of a "Special Energy Programme" in 1988 and was stopped due to civil war in Burundi in 1992.

After first experiences with family-sized biogas plants, the Burundian project started in 1987 to build medium scale biogas sanitation systems (50 m^3 to 250 m^3) connected to the toilets of boarding schools. Private contractors were commissioned for the plants. The training of craftsmen, the establishment of a service system and the set-up of material credit funds were to provide the basis for a self-reliant dissemination concept. By 1992, 206 small-scale biogas plants, and 84 institutional scale biogas sanitation plants (tunnel and fixed-dome plants) had been constructed (Kossmann 1996). Six out of ten households examined under the Biogas Survey in 1992 used liquid slurry as fertilizer. Outgoing from Burundi biogas sanitation units were also constructed in Bukavu Zaire/Kongo.

Standards for on-site household based "biodigester septic tanks and biolatrines" were developed in 2000 by the GTZ and DED[3] supported Ethiopian Project LUPO (Land-Use Planning Oromiya) and later were improved in Lesotho by the NGO Technology for Economic Development (TED) (Kellner 2002).

A document on the Biodigester Septic Tank (BST) was prepared in 2000 by the Scientific Research Council of Jamaica (Ministry of Land & Environment, 2002) and presented to the Ministry of Commerce and Technology, the Ministry of Health, and the Ministry of Land & Environment/Ministry of Water & Housing for approval to be used as the system for future on-site sewage treatment for housing developments. In the following years a wide range of requests were received from housing developers to utilise the biogas technology (with fomer GTZ support developed Biodigester Septic System) for the on-site treatment of domestic sewage for urban, suburban and rural housing, thus replacing septic tanks and soak-away pits (Williams 2004).

The Bremen Overseas Research and Development Assocation's (BORDA) approach from 1998 for Decentralised Wastewater Treatment Systems (DEWATS) integrates biogas digesters as one pre-treatment module. DEWATS linked biogas digesters have shown significant benefits, increasing the overall sustainability of DEWATS sanitation projects, especially projects addressing sanitation infrastructure in low-income settlements and smaller institutions. The resources recovered from these biogas

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[1] http://www.fcs.uga.edu/pubs/current/C819-2.html

[2] http://www.unicef.org/india/overview_4457.htm

[3] DED = German Development Service (www.ded.de).

digester settings (gas for cooking, heating or lighting) when combined with adequate social interventions have resulted in increased acceptance of the installations by communities and institutions. BORDA e.V. is promoting in general the biogas settler as the unique biogas tight energy collecter within their treatment concept while other institutions like the Biogas Institute of the Chinese Ministry of Agriculture (BIOMA) and the Indian Ecosan Service Foundation construct their entire system to collect as much biogas as possible from all anaerobic treatment steps in a DEWAT-System.

The Lesotho NGO Technology for Economic Development (TED) was founded in January 2004 as a successor of the Lesotho Biogas Technicians Self Help Group. With the TED specific technical design – and incorporating wastewater into the feeding material – a solution for one of the most pressing problems for households - lack of water and yearly emptying of septic tanks - was found. Up to 2010 more than 140 biogas sanitation systems of varying sizes were built and all of them are still in operation. The TED–bio-sanitation-digester system combined with DEWATS elements proved to be especially suitable for wastewater treatment; it works well on household and settlement level. Today, biogas sanitation in Lesotho is a technological package where wastewater and other organic matter are treated biologically in a bio-digester producing gas as an energy source and water as fertilizer or sludge as soil conditioner or fertilizer. The system is found appropriate for the capital Maseru and the district towns as many households and institutions have serious problems, and high cost burden with the disposal of their sewage.

Pure biogas sanitation systems are now in operation in many countries around the world such as Barbados, Bangladesh, Bolivia, Burundi, Buthan, Cameroon, China, Democratic People's Republic of Korea, Ethiopia, Georgia, India, Indonesia, Jamaica, Kenya, Laos, Lesotho, Marrocco, Mozambique, Nepal, Nicaragua, Philippines, Republic of Korea, DPR Korea, Rwanda, South Africa, Tanzania, Thailand, Uganda, Vietnam and Zambia.

2.5 Applications of biogas sanitation

Biogas sanitation systems are typically used as part of an on-site household-based, decentralised or semi-decentralised wastewater treatment processes.

They have been used to treat:
1. Domestic wastewater
2. Organic waste
3. Brown water
4. Blackwater
5. Excreta
6. Faeces
7. Faecal sludge

Biogas sanitation systems are usually designed as:

- **primary treatment** for removal of settleable and digestable solids and organic matter (biogas settler, biogas septic tank), the primary treatment could be divided in multiple anaerobic steps i.e. as "biogas settler followed by anaerobic baffled reactor",
- **secondary treatment** for nutrient removal (nitrogen), hygienisation, and reduction of chemical oxygen demand (COD) and biological oxygen demand (BOD) – (anaerobic filter, upflow anaerobic sludge blanket reactor). Secondary treatment could further be carried out in a separate aerobic treatment process with natural aerated trickling filters, constructed wetlands or aerobic polishing pond systems.

2.6 Characteristics and definitions

The following characteristics were taken from Tilley *et al*. (2008).

Anal cleansing water is water collected after it has been used to cleanse oneself after defecating and/or urinating. It is only the water generated by the user for anal cleansing and does not include dry materials. The volume of water collected during anal cleansing ranges from 0.5 L to 3 L per cleaning.

Biogas is the common name for the mixture of gases released from anaerobic digestion. In conventional septic tanks, Imhoff tanks (combined settler and sludge treatment units) and anaerobic lagoons this biogas is vented out, creating climate critical emissions due to its methane content. The rate of methane production depends on the rate of removed COD and the temperature. It is also common to relate the production to the dry matter (DM) or organic dry matter (ODM) of the input material. In human faeces organic matter makes up to 86% of dry matter. Depending of the reactor type, rentention time and biodegradibility, about 40% to 90% of organic matter could be converted to biogas.

All the mentioned figures should considered that one adult on an meat based diet will produce from 100 to 250 grams of feces per day. On a vegetarian diet, an adult will produce from 300 to 600 grams per day (both with 24-27% DM). Therefore the biogas potential has to adopted locally on diet, age and climate. Normal values for urine are 1 to 1.6 litres volumes per day. (House, David 2006)

Common figures for biogas production are given below:

0.350 m^3CH_4/kg COD removed; or 1 kg BOD removed results in 0.35 m^3 methane at 273^oK and $p=p_o$; energy content of methane = 35,8 MJ/m^3. Based on Dutch figures the production of black water and organic kitchen waste is 100g BOD per person per day results in 35L methane per person per day (Zeeman, Grietje 2006).

Based on Nepal figures 27L biogas from faeces per person per day are produced under operational temperatures of 26-30oC, including organic kitchen waste it increases to 62L biogas per person per day, with a methane content ranging from 57% to 78%. (Red Cross, Nepal 2009).

Out of feaces with organic dry matter (ODM) content of 93%: 0.450 m3 biogas /kg ODM or 0.290 m3 methane/kg ODM or 0.210 kg methane/kg ODM may be produced. (Jekel, Martin 2006)

Blackwater is the mixture of urine, faeces and flushwater with anal cleansing water and/or dry cleansing material (such as toilet paper). Blackwater contains all of the pathogens of faeces and all of the nutrients of urine diluted in flushwater or anal cleansing water. As part of a research project in Freiburg, Germany, it was found that for direct biogas production from brown water the high nitrogen concentrations in the black water (urea is cleaved by the enzyme urease to CO2 and ammonia, which is one of the most powerful cell poisons.) Fermentation process can come to a halt (auto-intoxification). Remedy: separation of urine, or solid / liquid separation of black water and digestion of the solid (brownwater or sludge) phase. (Braun 2003, and Snell 1943)

Brown water consists of faeces and flushwater; in practice there is always some urine contained, as only 70–85% of the urine is diverted. Brown water is generated by urine diversion flush toilets; the amount depends on the volume of the flushwater used. If the urine is separated, the nutrient content is reduced. The pathogen and nutrient load of faeces is not reduced, only diluted by flushwater and anal cleansing water.

Effluent is the general term for liquid that has undergone some level of treatment and/or separation from solids. It originates from either collection, storage and treatment or a (semi-)centralised treatment technology. Depending on the type of treatment, the effluent may be completely sanitised or may require further treatment before it can be reused or finally disposed.

Excreta consists of urine and faeces that are not mixed with any (flushing) water. Excreta is small in volume, but concentrated in nutrients and pathogens. Depending on the faeces it is solid, soft or fluid.

Faecal sludge (night soil) is the general term for the raw (or partially digested) slurry or solid that results from the storage of blackwater or excreta. The composition of faecal sludge varies significantly depending on the location, the water content, and the storage. For example, ammonium (NH_4-N) can range from 300-3000 mg/L while helminth eggs can achieve to 60,000 eggs/L. The composition determines the appropriate type of treatment and reuse.

Faeces refers to (semi-solid) excreta without urine or water. Each person produces approximately 50L per year of faecal matter. Of the total nutrients excreted, faeces contain about 10% N, 30% P, 12% K and have 10^7–10^9 faecal coliforms /100 mL.

Flushwater is the water that is used to transport excreta from the user interface (toilet) to the storage or treatment point. Freshwater, rainwater, recycled greywater, or any combination of the three can be used as flushwater source.

Organics refers here to biodegradable organic material that could also be called biomass or green organic waste (including kitchen waste). Organic degradable material could include leaves, grass and market wastes.

Figure 2. Construction of fixed dome household biogas plants for animal manure, which have toilets connected as well (near Hanoi, Vietnam). (source: F. Klingel, 2008).[4]

Treated sludge is the general term for partially digested or fully stabilised faecal sludge. The USA Environmental Protection Agency has strict criteria to differentiate between degrees of treatment and consequently, how those different types of sludges can be used. “Treated sludge” is used as a general term to indicate that the sludge has undergone some level of treatment, although it should not be assumed that treated sludge is fully treated or that it is automatically safe. It is meant to indicate that the sludge has undergone some degree of treatment and is no longer raw. Also anaerobically treated sludge may be post-treated again to reach higher sanitization degree and to separate remaining water content by drying in leachate beds, sludge soilzation units, or through composting. Even traditional sludge methods can provide an effective barrier for mitigation the occupational health risks associated with untretaed fecal sludge reuse in agriculture (Razak 2010).

Figure 3: Glas fiber digester made in China (source: www.biogas.cn)

2.7 Basic principles of anaerobic digestion

2.7.1 Process fundamentals

Anaerobic digestion is a complex physical-chemical and biological process that takes place in the absence of oxygen. Due to the biological conditions this decompostion process is possible under anoxic (presence of nitrate) and anaerobic conditions: Organic substances are split by bacteria into components and components are “re-arranged”; bio-chemical degradation is originated by bacteria.

The digestion is a multi-stages process (consisting of hydrolysis, acid formation stage, methanogenesis) performed by different bacteria and microorganisms. In biogas sanitation systems, the different degrading reactions take place in one digester.

The digestion process starts with hydrolysis of the input materials caused by bacteria in order to break down insoluble organic polymers such as carbohydrates. Acidogenic bacteria then convert sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids; followed by acetogenic bacteria converting the resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide. At the end of the process, methanogens convert these products into methane and carbon dioxide.

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[4] Photos are from surroundings of Hanoi - population density is quite high there, and the people have cattle in the villages, which leads to pollution. In Vietnam and in Nepal there is a large and successful biogas support program from SNV (financed by KfW) See: www.biogas.org.vn/Web/Default.aspx. More photos: http://www.flickr.com/photos/gtzecosan/sets/72157613849109546/

In other words, the digestion process consists of the following three steps:

1. **Hydrolysis**: (i) the organic matter is hydrolysed by extracellular enzymes; (ii) bacteria decompose the long chains of complex to simpler substances, for example polysaccharide to monosaccharide
2. **Acidification**: (i) acid producing bacteria convert intermediate fermentation products into acetic acid, H_2 and CO_2; (ii) acid producing bacteria create anaerobic conditions for CH_4 (methane) producing bacteria
3. **Methanisation**: methanogens, methane producing bacteria; acetic acid and/or hydrogen is used to form methane. Sulfate reduction leads to the formation of hydrogen sulphide.

The anaerobic process could be inhibited by higher concentrations of for example: ammonia[5], heavy metals, light metal cat-ions, oxygen, short chain organic acids, other organic acids, and sulphides. Short term biogas productivity tests are available to investigate on this.

2.7.2 Parameters for monitoring anaerobic processes

Parameters for monitoring anaerobic processes are: organic dry matter, pH value, C/N ratio, redox potential, volatile fatty acids, moisture content of biogas, acidity and alkalinity, and substrate structure. Gas production can be used for monitoring, the solids content in the reactor is an important parameter too. For further details please refer to Gutterer et al. (2009).

The concentration of nitrogen in the blackwater could increase until interrupting the digestion process. Urea from the urine is transformed by enzymes to ammonia, carbon dioxide and ammonium. Urea will be toxic to the methanogenic bacteria (self-intoxification). However, the adaptation to ammonia concentrations of more than 5000 mg N/L is possible, so for suspended solids, toxic N concentrations may not occur at all. Solid/liquid separation to reduce urine in the blackwater - using separation methods as AQUATRON[6], filter bag (Vinnerås and Jönsson, 2002), settler, urine diversion toilets[7]; and then only the “solid” part (faecal sludge) is digested, or organic waste (kitchen waste) is added as carbon rich material - helps to avoid problems related to high concentrations of nitrogen right from the start.

It is always important to maintain by weight a carbon/nitrogen (C/N) ratio between 15-30:1 for achieving an optimum rate of digestion. The C/N ratio can be manipulated by combining materials low in carbon with those that are high in nitrogen[8]. If the C/N ratio is very high, N limitation could cause low gas production, since nutrients for the growth of anaerobic bacteria are lacking. If the C/N ratio is very low, the pH value may increase, and will have a toxic effect on bacteria, and also result in lower biogas production. (van der Wal 1979)

2.8 What should be done with the biogas?

2.8.1 Possible biogas uses

Practically most anaerobic bioprocesses stabilise organic wastes that are formed from mixtures of fats, proteins and simple carbohydrates and this typically results in biogas composition illustrated below.

- methane (CH_4): 50 - 70 vol.%
- carbon dioxide (CO_2): 28 - 48 vol.%
- other gases: up to 2 vol.%

including trace components as

- hydrogen
- nitrogen
- oxygen
- ammonia
- argon
- carbon monoxide
- hydrogen sulfide
- non-methane volatile organic carbons
- halo carbons

Biogas is used as an ecologically friendly and future oriented technology in many countries. The calorific value of biogas is about $6kWh/m^3$ - this corresponds to about half a litre of diesel oil. The net calorific value depends on the efficiency of the burners or appliances. Methane is the valuable component under the aspect of using biogas as a fuel [Kossmann, 1996]

Biogas can be used for (in order of simplicity, with simpliest option first): cooking with gas stoves, lighting, heating, electricity generation (with combined heat and power (CHP) units or fuel cells), cooling, or as transport fuel. Of course, the latter options are only feasibly for larger biogas systems.

Biogas cooking utensils

Biogas lamp

Figure 4: Biogas appliances (source: www.biogas.cn)

What can 1 m3 biogas do? (Amrit Kaki 1984)

- It can illuminate a gas lamp equivalent of 60 W non-electricity saving bulb for about 7 hours, resulting in a light performance efficiency of only 7%, 93% of the energy content is transformed in heat.
- It can cook 3 meals for a family of 5-6 persons.
- It can generate 2 kW of electricity, the rest turns into heat which can also be used for heating applications.
- It is average equivalent to 5.5 kg of firewood.
- It is equivalent to 1.5 kg of charcoal.
- It is equivalent to 0.45 litre of petrol, 0.55 litre of diesel, 0.60 litre of kerosene or of gasolene, or 0.5 kg of LPG

As far as plants operate only on pure faeces an increased sulphur content in the gas as result of an increased production of hydrogen sulphide (H_2S) has to be taken into account and possibbly filtered out or eliminated chemically. H_2S is a colorless gas having a strong odor of rotten eggs; it fatigues the sense of smell which cannot be counted on to warn of the continued presence of the gas. While the biogas is used for cooking the presence of H_2S in the biogas result

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[5] The reason why urine (which is converted to ammonium/ammonia) is not a problem in anaerobic treatment is described in the following Section 2.7.2.

[5] www.berger-biotechnik.com/downloads/aquatronhybridtoiletsystem.pdf

[7] For details on urine diversion toilets see another GTZ technology review on urine diversion components: http://www.gtz.de/en/themen/umwelt-infrastruktur/wasser/9397.htm

consequently in smell disturbance and faster corrosion of the cast iron burner parts which get in direct contact with biogas. Additionally a part of H_2S might be converted through the uncomplete combustion of biogas into sulphur dioxide (SO_2), which could results in headache and breathing problems. Even it is known that H_2S needs a lower (260°C) combustion temperature than Methane (CH_4) - at 560°C, temperatures over 850°C throughout the flame are nessesary to prevent the formation of carbon oxides, partially oxidised hydrocarbons, dioxins and furans, and polycyclic aromatic hydrocarbons (PAHs).

2.8.2 Flaring of biogas to avoide methane emissions (greenhouse gas)

Methane (CH_4) is a greenhouse gas that remains in the atmosphere for approximately 9-15 years. Methane is 21 times more effective in trapping heat in the atmosphere than carbon dioxide (CO_2) over a 100-year period and is emitted from a variety of natural and human-influenced sources. Human-influenced sources include landfills, natural gas and petroleum systems, agricultural activities, coal mining, stationary and mobile combustion, wastewater treatment, and certain industrial process. Methane is also a primary constituent of natural gas and an important energy source. As a result, efforts to prevent or utilize methane emissions can provide significant energetic, economic and environmental benefits. Under Indian conditions about 0.2kg CO_2-emission reduction per person and year may be generated from methane capturing biogas sanitation system by replacing open defecation (Olt, Christian 2008). CARMATEC in Tanzania demonstrated in a Project Idea note a possible 2 t/CO_2-emission reduction per person and year which may be generated from methane capturing biogas sanitation system replacing deep anaerobic lagoons (CARMATEC 2010).

Flaring of methane from septic tanks is never carried out because the amount of methane per household is small and small flares are not easy to maintain. But all septic tanks of a city taken together, the amount of methane could be significant in terms of greenhouse gas emissions.

Stoichiometrically 9.6 volumes of air per volume of methane are required to achieve complete oxidation by burning. For the typical biogas composition given above this ratio reduces to 5.7:1. Similarly the energy release by pure methane is 36 MJ m^3 (gross calorific value) and is reduced to 21 MJ m^3 for biogas.

Figure 5. Biogas cooker at Gachoire Girls High School in Gachoire, Kenya (source: S. Blume, 2009).

2.9 Financial and economic aspects

An understanding of financial and economic returns are key elements in the decision-making process about biogas sanitation. Financial analysis of costs and benefits provides insight into consumer willingness and ability to invest in biogas sanitation technologies by capturing potential net returns to the household.

"*The problem of a cost-benefit analysis of a sanitation system lies in the parameters influencing the calculation, which are often difficult to project a priori. A time frame of 20 to 30 years - the normal lifetime of a treatment plant - should constitute the basis for calculation. While construction costs are relatively easy to calculate, an estimate of realistic running costs would need an in-depth study of the technical requirements of the system as well as the prevailing social environment.*" (Sasse 1998)

Certain parts of the plant have to be replaced after 8 - l0 years, e.g. a steel gas holder. The steel parts need to be repainted every year or every second year. As a rule, real prices and interest rates should be used in a calculation. For cost calculation inflation rates are irrelevant as long as construction costs refer to one point of time. However, in calculating a cash reserves put aside for servicing and repair the inflation rate must be considered (Kossmann 1996).

A discussion paper prepared by Winrock International for the Dutch Ministry of Foreign Affairs presents as result for selected African countries that biogas sanitation could yield benefit-cost ratios (BCRs) ranging from 1.22 to 1.35 and financial internal rates of return (FIRRs) from 7.5% to 10.3% (Renwick 2007). This document lists also in detail the parameters that could be used internationally for objective comparison also with respect to the impact on the environment.

The cost per cubic meter of digester volume decreases as volume rises. Therefore, the appropriate size of the biogas plant should be estimated. This fact sheet can only provide an idea as it is based on different types of plants. Consequently, the following system is sufficient for a rough calculation of household based biogas sanitation systems:

- the cost of 6.5 sacks of cement x m3 digester volume plus,
- the cost of 5 days work for a mason x m3 digester volume plus,
- the costs of 100 m gas pipes (1/2"), plus,
- the costs of two ball valves (1/2"), plus,
- the cost of gas appliances which are feasible for this size.

The individual prices are to be determined for the project location. The sum then includes material and wages. The distance from the biogas plant to the point of gas consumption was assumed as being 25 m (the 100 m used in the calculation include costs for connectors and wages). Where greater distances are involved, the cost for gas pipes will have to be increased in proportion (Kossmann 1996 and Gutterer 1993).

The final decision of an investment in a sustainable sanitation model with biogas capture should be analysed in regard to the following criteria: (1) Investment cost efficiency, (2) Operating cost efficiency, (3) Operating convenience for the user, (4) Reliability, (5) Biogas Yield, (6) Space Efficiency, (7) Economic Benefits, (8) Water Saving, (9) Ecological and Environmental Benefits, (10) Marketability (Panzerbieter 2005).

2.10 Septic tanks

Synonymous terms to biogas sanitation system include biogas septic tank in which the anaerobic conditions are referred to as "septic" giving the tank its name.

Compared to a proper designed, operated and maintained biogas sanitation system, a typical septic tank system consists of a (baffled) water tight tank and a soak-away drain without any reuse of the pre-treated effluent and without capturing the biogas produced. Therefore, depending on soil conditions and groundwater level, the effluent of a septic tank can transport bacteria, viruses, household chemicals, and other contaminants into the groundwater causing serious environmental problems [9], and the released biogas participates in the climate emissions.

3 Advantages and limitations of biogas sanitation systems

3.1 Advantages of biogas sanitation systems

3.1.1 Advantages compared to aerobic wastewater treatment systems

The advantages of biogas sanitation systems include:

- Generation of clean energy for household use: after an initial investment in the system, there is less or no need to spend money on fuel, and no more smoke from wood or charcoal in the kitchen.
- Cooking on biogas is quicker and easier than cooking with firewood.
- Destruction of bacteria, viruses and helminth eggs in human and animal excreta. A farm with a biogas system is a cleaner and safer place.
- Production of safe fertilizers for use on the farm containing plant nutrients in an easy absorbable liquid form.
- Support the fight against global warming by facilitating to burn methane from organic waste, instead of escaping into the atmosphere where it adds to the greenhouse effect; supports also efforts to restrict deforestation.
- Cost effectiveness: Biogas septic tanks have at least the same investment as a conventional septic tank, and capture the biogas for further use. Operation and maintenance expenses (energy and supplies) are low and require only low skilled labour. For financial consideration the energy source that is replaced by biogas is important (wood, kerosene, LPG).
- Low-tech system: Anaerobic technology does not rely on complex machines and processes (such as aeration systems); systems, such as the anaerobic pre-treatment units (settler, baffled reactors or filters) of a complex decentralized wastewater treatment system, require low but adequate maintenance.
- Low space requirement: underground construction does not occupy valuable space especially in urban areas; only 0.5-1m^2 per m^3 daily flow are needed, compared to 25-30 $m^2/m^3/d$ flow in aerobic ponds and constructed wetlands (Gutterer, Panzerbieter et al., 2009). The space above a biogas plant could also be built on as parking area, as long as the system remains accessible.
- Treatment capability for a wide variety of domestic and industrial effluents, especially suitable for wastewater high in organic matter.
- Multi-step decentraliced wastewater treatment systems does not need electricity if there is suitable slope for gravity flow, saving a large amount of investment into the sewerage system. Low energy and maintenance cost, low total lifetime cost.
- If well designed, constructed and operated, calculated sewage sludge production is five times less compared to aerobic systems. The sludge yield from anaerobic treatment is approximately 0.1kg VSS/kg COD removed; by contrast aerobic activated sludge treatment results in 0.5kg VSS/kg COD removed.
- As the anaerobic treatment alone can not meet the requirements of direct discharge into water bodies, a post-treatment with an aerobic process is necessary. But even this combination reduces the specific sludge production by 40% (Gasparikova et al., 2005).

Biodigesters offer a variety of benefits in ethical treatment of human waste. The most important consideration, which has not necessarily always been effectively managed, is the danger pathogens in human waste pose to health. These systems are scalable from the household, community level to the larger industrial scale applications. Successful applications can be found worldwide and as well as in history. Best of all, Anaerobic Digestion offers to turn waste into a resource. (Appropedia)

3.1.2 Reuse of digested sludge

Sanitation has a strong link to agriculture, as the nutrients such as nitrogen, phosphorus and potassium contained in human excreta are suitable as fertiliser, and the organics as soil conditioner. Biogas sanitation contributes to closing the nutrient cycle which is a target of sustainable agriculture. Each day, one adult excretes about 30g of carbon (90g of organic matter), 10-12g of nitrogen, 2g of phosphorus and 3g of potassium. Studies carried out under Prof. Dr. Ralph Otterpohl (Technical University of Hamburg-Harburg) revealed that in human excreta most of the organic matter is contained in the faeces, while most of the nitrogen (70-80%) and potassium are contained in urine. Phosphorus is equally distributed between urine and faeces. (Source: Otterpohl, Ralph 2002)

It has been calculated that the fertilising equivalent of excreta is nearly sufficient for a person to grow its own food (Drangert 1998). In reality, part of this potential is lost, during storage and treatment (such as nitrogen loss through ammonia volatilisation).

Treated excreta may serve not only a fertiliser; its organic matter content, which serves as a soil conditioner and humus replenisher – an asset not shared by chemical fertilisers – is of equal importance. Traditional practices esp. in South Asia of recycling faecal sludges to agriculture and aquaculture have ever since made use of this resource. Urban farmers in arid and semi-arid zones or during dry seasons are still using wastewater, raw or treated, for irrigation to minimise the purchase of chemical fertiliser.

Recycled sludge and water might still contain germs. For re-use in agriculture and gardening specific sanitization performance of the chosen systems and post-treatments should be considered. Please refer to details in Table 2. Nevertheless, agricultural and gardening experts' advice is required to optimize seasonal application and quantities related to cash crops, flowers and trees.

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[9] www.waterencyclopedia.com/Re-St/Septic-System-Impacts.html

3.2 Disadvantages of biogas sanitation systems

3.2.1 Incomplete pathogen removal

Human excreta are contaminated with all kinds of pathogens and hence a reliable technology is necessary for their inactivation. During anaerobic digestion an inactivation of most animal and plant pathogens is obtained under thermophillic conditions (>55℃ for several days). Several studies on wet fermentation report that also mesophilic and lower temperature operation inactivates pathogens; further findings indicate that reactors with retention times of at least 60 days at 20oC to 15 days and 35-55oC reduce significantly any type of pathogens (Michael H. Gerardi 2005).

Table 1. Effects of anaerobic batch sanitisation on selected pathogens and parasitic ova as well as on E. Coli indicator

Pathogens & parasitic ova	Thermophilic fermentation (53-55℃)		Mesophilic fermentation (35-37℃)		Ambient temperature fermentation (8-25℃)	
	Days	Fatality (100%)	Days	Fatality (100%)	Days	Fatality (100%)
Salmonella	1 – 2	100	7	100	44	100
Shigella	1	100	5	100	30	100
Poliviruses			9	100		
E-Coli titre	2	$10^{-1} – 10^{-2}$	21	10^{-4}	40 - 60	$10^{-4} – 10^{-5}$
Schistosoma ova	Several hours	100	7	100	7 – 22	100
Hookworm ova	1	100	10	100	30	90
Ascaris ova	2	100	36	98.8	100	53

(*source: Yongfu, Y., Yibo, Q., Yunxuan, G., Hui, Z., Yuansheng, X., Chengyong, X., Guoyuan, F., Jiequan, X. and Taiming, Z. (1992), The Biogas Technology in China. Agricultural Publishing House, China, ISBN 7-109-01777-X*)

Many studies reveal also that under fully mixed mesophilic conditions, pathogens are not completely inactivated. Therefore recommendations on the use of the not post-treated slurry should limit irrigation only to fruit trees, and exclude spray irrigation to vegetables. Effluent water could be post-treated with UV desinfection by natural sunlight in shallow polishing ponds. Post-composting of sludge may be required for a one year period. If the effluent is directly worked into the soil as soil conditionner no further restriction applies.

Two main factors regulating the inactivation of pathogens have been identified, namely the temperature and the concentration of free ammonia as a function of the time of treatment/exposure. The post-treatment alternatives presented here (composting, anaerobic digestion, ammonia treatment, land application) all have their advantages and disadvantages depending on local conditions, the material to be treated, and the intended use of the end product. Therefore, prior to selection of treatment method it is necessary to evaluate the specific local conditions, and to define how the end-product is to be used as a fertiliser, according to hygiene risk of the crop.

Table 2: Overview on post-treatment options

Post-treatment	Frame conditions	Effect	Advantage	Disadvantage
Composting	The higher the temperature, the shorter the time needed for treatment. WHO gives a recommendation of a minimum one week of treatment <u>above</u> 50 ℃ for composting of faecal matter. Alternate composting platforms or -pits for batchwise management.	May give good hygienic quality. Temperature/time dependent.	Low-tech equipment possible. May degrade organic pollutants.	Labour-intensive. Eutrophying emissions. Risk for regrowth. Leaching water effluent (may be reused for digestion).
Further anaerobic digestion steps for liquid effluents (AF, ABR)	During mesophilic anaerobic digestion many pathogenic and indicator bacteria, as well as some viruses, need more than 2 days for a 1 $\log^{10}$ reduction. Thermophilic digestion of sewage sludge in a large-scale continuous process reduces indicator bacteria and Salmonella sufficiently. On the other hand, mesophilic digestion has proven to be more efficient in degrading organic pollutants such as benzoic acid, m- and p-cresol compared with thermophilic digestion. By using a process adapted for high ammonia content ($8\ g\ L^{-1}$) at a pH close to 8, it is possible to have a sanitising mesophilic process.	May give good hygienic quality. Temperature/time dependent.	More valuable energy produced. Mesophilic treatment degrades organic pollutants. The evaluation of biogas itself always indicated a low risk regarding disease transmission.	Risk for regrowth and methane emissions.
Ammonia treatment	Ammonia is added either as aqueous ammonia solution or as granulated urea. This treatment is efficient for inactivation of bacteria, parasites and some viruses. Recommended treatment is either 0.5% NH_3 for one week, or 2% urea for two weeks at temperatures above 10 ℃, or for one month at temperatures below 10 ℃. Covering needed to avoid ammonia emissions	Gives good hygienic quality. pH and uncharged NH_3 dependent.	Low-tech equipment needed. Ammonia recycled as a fertiliser.	Low risk for regrowth.
Land application	May be spread-on, subsurface drainages or worked-in.	Only application weeks before planting or seeding, or before winter.	Studies have shown a more rapid reduction in the Soil (“worked-in”), in general enteroviruses seem to be reduced faster than indicator bacteria.	Needs storage capacity. Survival of pathogens in soil, grass and silage for close to 2 months has been shown under laboratory conditions and survival on soil and biosolids for over one year has been proven (spread-on, sub-surface drainages).
Sludge drying bed	If the slurry is not used directly used, it may be collected and treated in sludge drying beds. Partially dig up the ground and pile up the excavated soil to earthen bunds. Alternate composting platforms or -pits for batchwise management.	May give good hygienic quality. Temperature/time dependent.	Low-tech equipment possible. Perimeter bunds will help in keeping surface run-off water from entering the sludge drying beds	Low risk for regrowth. Should be rainwater dilution protected Not applicable in monsoon areas

Above table was compiled with information from: *(a) Ann Albihn (National Veterinary Institute, Uppsala, Swede) and Björn Vinnerås (Department of Biometry and Engineering, Swedish University of Agricultural Sciences, Uppsala, Sweden), Biosecurity and arable use of manure and biowaste — Treatment alternatives, Livestock Science 112 (2007) 232–239*, available online at www.sciencedirect.com and *(b) J. Heeb and M. Wafler (2006) Face-to-Face Training Course “Capacity Building for Ecological Sanitation” Small-Scale Biogas Sanitation Systems, Network for the Development of Sustainable Approaches for Large Scale Implementation of Sanitation in Africa (NETSSAF), EU-Coordination Action Proposal/Contract Number: 037099* www.netssaftutorial.com

3.2.2 Temperature dependence

Organic material degrades more rapidly at higher temperatures because all biological processes operate faster at higher temperatures up to 65℃. The three ranges of temperature in which methanogens work are called psychrophilic (8-25ºC), mesophilic (30-42ºC) and thermophilic (50-65ºC). Biogas sanitation is often applied in countries where the ambient average temperature ranges above 15℃. In temperatures below 8ºC digestion capability is very reduced. The process is also sensitive to temperature variations of more than 3ºC; therefore variations have to be kept in a limited range to ensure a steady biogas production. The higher the process temperature the more sensitive is the process (bacteria).

Still very little work has been done regarding the production of biogas at psychrophilic temperatures. At 20 day HRT, propionate concentration has been reported to be about three times higher than that of acetate, whereas at higher HRT acetate and propionate maintained at almost equal concentrations. It is concluded that anaerobic digestion of human excreat can be carried out at 10℃ using adapted inoculums. Below 20℃ methane production starts only with the addition of temperature adopted inoculums, as the practical expereicne of TED-Lesotho has shown. Research results at the Wageneingen Unversity in The Netherlands from 1991 showed a stable digestion process at a process temperature of 15 0C and an HRT of 100 and 150 days. The COD reductions were only 14 and 18 percent respectively. (Balasubramaniyam 2008)

To improve biogas sanitation systems the application of insulation (above and below ground), combined greenhouse application, keeping the plant environment dry, active and/or passive heating of plant and substrate should be considered, depending on available construction material, design experiences, funds and micro-location. Appropriate technical solution should by done with the support of experienced experts. The optimal storage design volume (HRT) has to consider the coldest winter conditions, but the post-treatment choice the seasonal reuse options.

3.2.3 Variable performance

Performance may be less consistent than in conventional (aerobic) treatments. In terms of removal of organic matter and nutrients, biogas sanitation is mainly a primary or secondary treatment step, which may need post-treatment depending on the disposal or reuse strategy. The biological components are sensitive to toxic chemicals, such as ammonia and pesticides. Flushed pollutants or surges in water flow could temporarily reduce treatment effectiveness. Therefore buffer tanks or biogas-settler as pre-treatment units for wastewater flow equalisation should be built.

As effluent from anaerobic reactors will usually require further treatment prior to discharge to surface or underground water bodies, this depends also on the loading rate of the reactors. At organic loading rates between 1 and 4 kg COD per m^3 reactor and day, the highest removal rate is at 1 and drops to 4. Therefore 1 may be selected as the optimum loading rate. The authors have drawn the assumptions, that if the organic load can be removed anaerobically, it is almost in any case more economical to increase the size of the anaerobic reactor, rather than to increase the aerobic post-treatment step.

3.2.4 Experienced constructions, design and maintenance staff required

People with experience to design, build and maintain biogas sanitation systems are required at local level. A biogas sanitation system is technically more complicated as it includes more components than just a (urine diversion dehydration) toilet. Main considerations for a technical design includes substrate's property (daily flow and peak flows, flush water consumption, type and quantity of feedstock, Chemcial Oxygen Demand (COD), Dry Matter (DM) and Volatile Solids (VS)), expected operation data (temperature, pH, Organic Load Rate (OLR), Hydraulic retention time (HRT), Sludge retention time (SRT)), performance expectation (methane production, COD_t removal, required biogas storage volume), post treatment requirements (digestate property (DM, COD, VS) and sludge disposal or reuse (DM, VS, composting temperature, available drying surface, leachate recycling) and remaining agricultural nutrients (Nitrogen (N), Phosphour (P), Potassium (K). Special training on biogas sanitation design and engineering is offered through BORDA (www.borda-net.org), Indian Ecosan Service Foundation (http://ecosanservices.org), Technology for Economic Development (TED)-Lesotho (www.ted-biogas.org), Centre for Sustainable Environmental Sanitation (CSES) at the University of Science and Technology Beijing (USTB) (www.susanchina.cn), and at the University of Life Science (UMB) Norway (www.ecosan.no).

3.2.5 Risk of explosion

As methane is flammable, there is always a small but manageable risk of explosion if methane escapes. The Flammable Range (Explosive Range) is the range of a concentration of a gas or vapor that will burn (or explode) if an ignition source is introduced. Below the explosive or flammable range the mixture is too lean to burn and above the upper explosive or flammable limit the mixture is too rich to burn. The limits are commonly called the "Lower Explosive or Flammable Limit" (LEL/LFL) and the "Upper Explosive or Flammable Limit" (UEL/UFL). For methane the LEL is 5%, the UEL is 15%, H_2S- LEL is 4.3%, H_2S-UEL is 46%.

4 Overview of main types of biogas sanitation digesters

4.1 Classification of biogas sanitation systems

Biogas sanitation systems can be classified according to various parameters; the three most important design criteria are (1) hydraulic retention time (HRT in days), (2) organic load rate (OLR in kg COD/m^3 active fermenter volume), and (3) sludge retention time (SRT in days or years).

Table 3: Overview on biogas sanitation systems

Type of digester	Expected BOD reduction	HRT (days)	OLR (kg COD/ m^3)	SRT (days)	optimal application
biogas septic tank (BST) / biogas settler (BS)	25-60%	minimum 20, optimum 60 (limited by construction costs, but longer HRT for sanitization required)	0.5 – 2	miniumum 10 days, maximum 7 years (as higher to lower sludge volume handling challenges)	Pretreatment, energy optimized with organic wast as coferment, baffle in BS required if built as main treatment system with post-composting, post-wetland, or drying bed
Anaerobic baffled reactor (ABR)	70-90%	2 - 4	1 - 12	At least 2 years	Post-treatment after BS (than without bafle)
Anaerobic filter (AF)	70–95%	0.5 - 4	5 - 15	Theorethicall no, but sludge may accumlate at the bottom	Post-treatment after BST or after ABR
Upflow anaerobic sludge blanket (UASB)	55-90%	0.5 - 10	15 - 32	more than 365 days	Main-treatment after grid chamber, energy optimized with organic waste as co-ferement, or post-tretament after BS or BST, with post-wetland, or post-lagoon

(source: H.-P.Mang)

The required *hydraulic retention time* (HRT) of the substrate in the digester depends on the process temperature and the type and concentration of the mixed substrate itself. This will then determine the volume of the digester. Digesters are designed for an optimum economic balance between gas yield and volume (HRT). Therefore the retention time is chosen as the total time required to produce a certain amount of the total gas (to size the digester to obtain all possible biogas is often not economic). In a biogas-sanitation system the overall HRT should not be less than 20 days due to methanogenic bacterial reproduction time, but from a health point of view the HRT should be extended to at least 60 days, if no adwquate post-treatment is foreseen. In this case the volumetric load may not exceed 2 kg of COD per m^3 of active digester volume.

A *sludge retention time* (SRT) of at least 10 days is necessary to promote methanogenesis in the anaerobic treatment of primary sludge at a process temperature of 25℃ (Miron 2000) while a SRT of 15 days is necessary for sufficient hydrolysis and acidification of lipids. For temperatures as low as 15℃, a SRT of at least 75 days has to be considered to achieve methanogenic conditions (Zeeman 2001). As longer the SRT as better will be the degradation and stabilization of the sludge and less sludge will remain. This is important for bigger units (at prisons or schools); the handling of sludge can be also a problem in dense populated areas.

Different types of biogas sanitation units could be combined with each other (so called combined systems, multi-step systems or decentralized wastewater treatment systems) in order to benefit from the specific advantages of the different systems. The quality of the final effluent from the systems improves with the multiple steps of the treatment facility. Design information of the recommended four design variations are available through many websites and literature (see Section 6) and expert consultations.

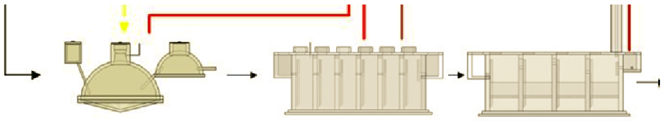

Figure 6: combination example of biogas settler (without baffle), anaerobic baffled reactor and anaerobic filter, where blackwater flows in the biogas settler and greywater in the anaeribic baffled reactor (source: teaching material of the Indian Ecosan Service Fundation www.ecosanservices.org)

Local design and engineering adaptations to local human diet (organic load and biogas potential), hygienisation needs (household or community) and effluent reuse (energy plants, tree nursery, grasland, vegetable, grain) are always nessesary. Therefore the following sectors can only provide an introduction to the different biogas sanitation systems.

4.2 Biogas settler (BS) or biogas septic tank (BST)

The biogas settler (BS) (with or without baffle(s), depend of the further treatment step choosen) or biogas septic tank (BST) (always with integrated baffles) is mainly applied as on-site household based system with secondary treatment of effluents in compost (solids) and drainages/subsurface irrigation (liquid). The direct effluent from the reactor, a dark slurry, is a nutrient-rich fertiliser for agriculture and aquaculture, due to the conservation of nitrogen during the anaerobic process. Any kind of suitable organic waste (for example kitchen waste) could be added to increase the biogas yield. BS are also applied as a pre-treatment step in combined anaerobic/aerobic multi-step systems and as pre-treatment in combination with constructed wetlands.

Generally, the removal of 65% of solids, up to 60% of biochemical oxygen demand (BOD) and a 1-log removal of *E. coli* can be expected in a well designed biogas septic tank although efficiencies vary greatly depending on operation, maintenance, and climatic conditions. BSTs can be installed in any type of climate although the efficiency will be less in cold climates. Although a BST is gas and watertight, it should not be constructed in areas with frequent flooding.

In a biogas settler (BS), to achieve that the sludge retention time (SRT) is longer than the hydraulic retention time (HRT), a baffle or a separation wall should be added when it is operated as stand alone system. The accumulated settled sludge must be removed from the base of the BS periodically, based on experiences this will be nessesary every 5-7 years. For domestic wastewater and blackwater the typical specific settled sludge generation is about 0.0037 l/g of Biological Oxygen Demand (BOD) reduction, under the assumption that the supposed ratio COD/BOD is 2:1.

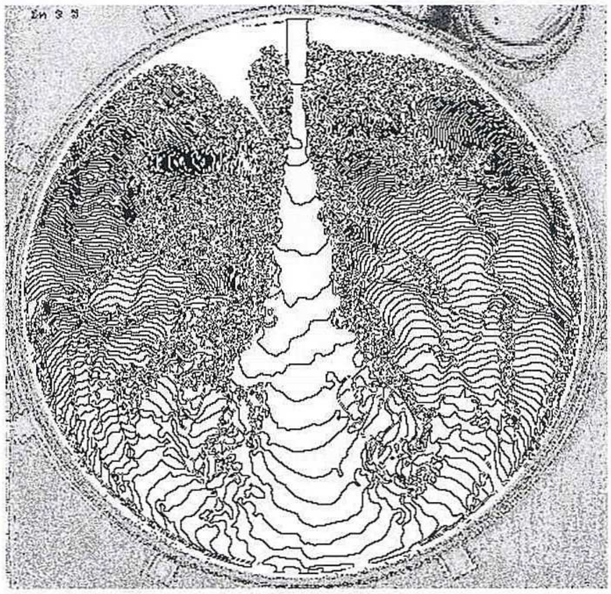

Figure 7: Linear overlay of the circular coils advancement from above in biogas digesters with flat bottomand without baffle (source: University of Oldenburg 2004)

Many different forms of constrution are known, for example: fixed-dome plant, bag digester, glass fiber (half) bowl plant, water jacked floating drum, PE or PVC predesigned tanks, covered anaerobic lagoons. Main parameters for the choice of construction material and for the basic design are (Kossmann 1996):

- Technical suitability (stability, gas- and liquid tightness);
- cost-effectiveness;
- availability in the region and transport costs;
- availability of local skills for working with the particular building material.

Figure 8. Maintenance of biogas settler at Naivasha bus park in Kenya: Cleaning of the manhole of the biogas settler from old clay to prepare for re-sealing (source: C. Rieck, 2009)[10].

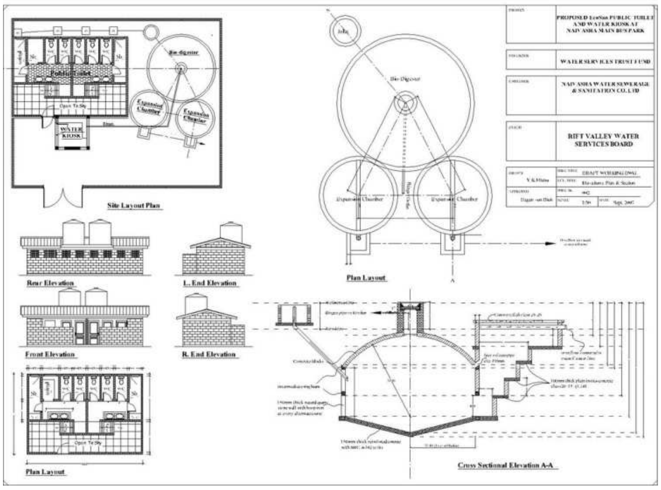

Figure 9. Technical drawing of the biogas settler without baffle shown in previous figure (source: C. Rieck, 2009).

4.3 Anaerobic baffled reactor (ABR)

The anaerobic baffled reactor (ABR) consists of a series of chambers in which the wastewater flows up-stream. Here, the suspended and dissolved solids in the pre-settled wastewater undergo anaerobic degradation. The activated sludge settles down at the bottom of each chamber and the influent wastewater is forced to flow through this sludge blanket where anaerobic bacteria make use of the pollutants for their metabolism. In practise the number of upflow-downflow-chambers should be 6 at minimum. This configuration provides a more intimate contact between anaerobic biomass and wastewater thus improving the treatment performance. Progressive decomposition occurs in the successive chambers. In ABR plants the BOD reduction rate is up to 90% and the pathogen reduction ranges between 40 - 75%. The baffled reactor is resistant to shock load and variable inflow. It operates by gravity and maintenance is reduced to desludging of the chambers at intervals of 2-3 years. Sub-soil construction of the module saves space.

Figure 10: TED-BORDA Anaerobic Baffled Reactor in Maseru, Lesotho, 2009 (source: TED)

Constructive separation of the sludge retention time (SRT) from the hydraulic retention time (HRT) is the key to the successful operation of an ABR. Due to this fact, a baffled reactor is considered as the best alternative to aerobic treatment and posterior to primary settlement in a biogas digester. Critical design parameters include peak flow, hydraulic retention time (HRT) between 2 to 4 days, and uplow velocity of 0.3m/h (Xanthoulis 2008), or 0.6m/h (AKVOPEDIA – Sanitation Portal) to a maximum of 1m/h (Ulrich 2010) are the main key parameters for the design dimensioning.

Depending on the local climate protection policy, the legal framework, and the limited technical capacity of designer and constructors, ABRs are often built without biogas capture. The amount of methane produced is related to the degradation of the biological oxygen demand (BOD) in the reactor, capturing of methane may be interesting under climate protection consideration.

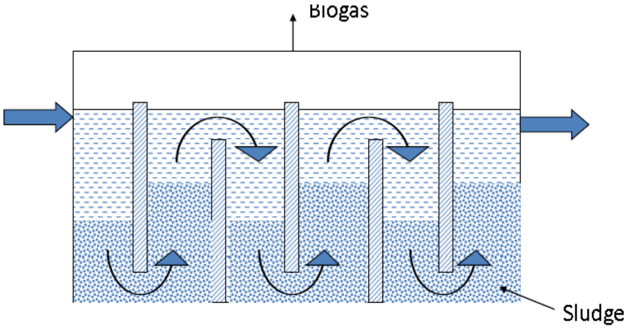

Figure 11: ABR design (Source: Paradigm Environmental Strategies, Bangalore, website: www.ecoparadigm.com)

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[10] For futher details see SuSanA case study on Naivasha bus park in Kenya: http://www.susana.org/lang-en/case-studies/technology/biogas

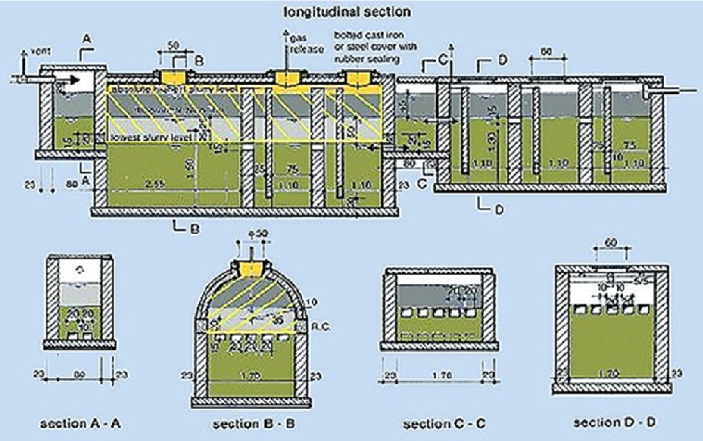

Figure 12: Gastight Anaerob Baffled Reactor with gas-tight pre-settlement and non-gas tight post-treatment (source: http://www.borda-net.org/modules/cjaycontent/index.php?id=29)

4.4 Anaerobic filter (AF)

The anaerobic filter (AF) is suitable for effluents with a low content of suspended solids and a narrow COD/BOD ratio, for instance from biogas settlers or biogas septic tanks or anaerobic baffled reactors as first treatment units. The bacteria in the filter are immobile and generally fix themselves to solid particles (carrier material) or to the reactor walls. Filter materials like rocks, cinder, plastic, or gravel provide additional surface area for bacteria to settle. The larger surface area for the bacterial growth helps in the quick digestion of the wastes. A good filter material provides a surface area of 90 to 300 m^2/m^3 reactor volume[11].

Anaerobic filters are reactors consisting of supporting material layer. On the surface of these material layers or bed fixation of microorganism the development of biofilm takes place. Anaerobic filters can be applied not only for treating concentrated wastewater but also for those wastewaters that have low organic load; they function efficiently for diluted sewage. In case of concentrated sewage the risk of blockage of the filter material increases with the concentration of suspended solids. They are best suited for post-treatment.

The Anaerobic Filter can be operated in either up-flow or down-flow or combined. In practise at least 4 chambers should be considered. The up-flow mode is recommended because there is less risk that the fixed biomass will be washed out. The water level should cover the filter media by at least 0.3m to guarantee an even flow regime.

The HRT and the peak flow are the most important design parameter influencing filter performance and number of chambers. An HRT of 0.5 to 1.5 days is a typical and recommended. Suspended solids and BOD removal can be as high as 85% to 90% but is typically between 50% and 80%. Nitrogen removal is limited and normally does not exceed 15% in terms of total nitrogen (TN). (AKVOPEDIA – Sanitation Portal)

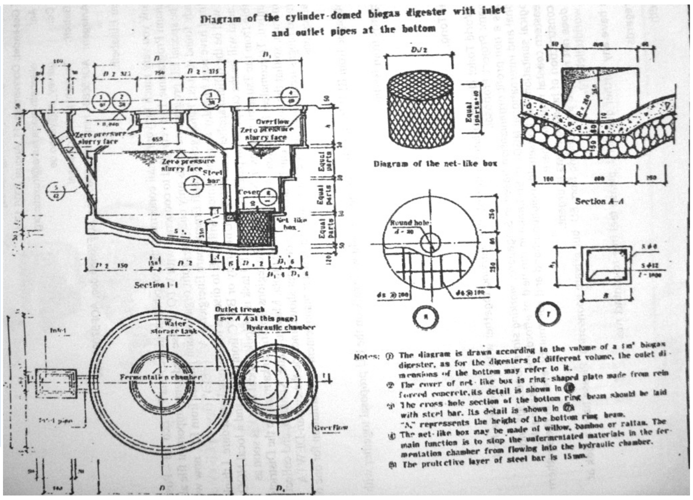

Figure 13: Design sketch of a chinese biogas sanitation digester GB 4750-84 combined with anaerobic up-flow filter in the outlet (source: Qiu 2002)

Problems could occur with clogging carrier material or uneven distribution of the wastewater on the material. If a fixed bed reactor (=anaerobic filter) has to be taken out of operation the re-establishment of the bacterial film need at least 6 months. To investigate the operational inside in the fixed bed is very diffcult. It is also possible that at the bottom of the fixed bed reactor a mineralized sludge bed accumulates. Further investigation during the start-up has to focus on the amount of effluent to be recirculated for a optimized degradation.

Authors' experience shows that there is no difference in removal rates between UASB and fixed bed reactors. The key to the optimal operation of a reactor is to understand the bacteria inside the reactor (how much, how active, how good in resisting shock loads).

Same as for anaerobic baffles reactors, depending on the local climate protection policy, the legal framework, and the limited technical capacity of designer and constructors, AFs are often built without biogas capture. The amount of methane produced is related to the degradation of the biological oxygen demand (BOD) in the reactor, capturing of methane may be interesting under climate protection consideration.

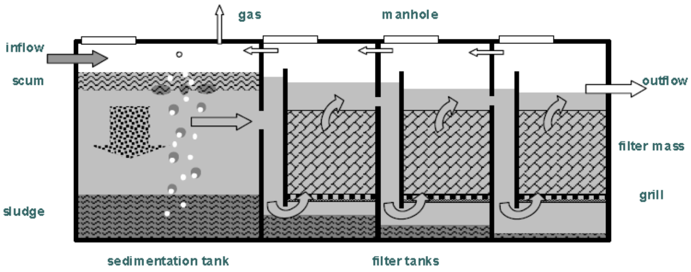

Figure 14: AF design with pre-settlement tank (Source: Sasse 1998)

4.5 Upflow anaerobic sludge blanket reactor (UASB)

The upflow anaerobic sludge blanket reactor (UASB) is a tank filled with anaerobic granular or flocculant sludge with good settling properties (the bacteria spontaneously agglomerate to form granules). Influent wastewater is distributed at the bottom of the UASB reactor and travels in

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[11] http://www.thewatertreatmentplant.com/anaerobic-filters.html

an upflow mode through the sludge blanket. The anaerobic degradation of organic substrates occurs in this sludge blanket, where biogas is produced and serves to mix the contents of the reactor as they rise to the surface[12].

The UASB reactor has the potential to produce higher quality effluent than biogas septic tanks, and can do so in a smaller reactor volume. The design of an UASB reactor must provide an adequate sludge zone since most of the biomass is retained there. The sludge zone is completely mixed because the wastewater is fed into the reactor through a number of regularly spaced inlet ports (Liu and Liptak, 1999). The UASB is also characterised by a much longer SRT in comparison with the HRT. An up-flow velocity of 0.6 to 0.9m/h must be maintained to keep the sludge blanket in suspension. (AKVOPEDIA – Sanitation Portal)

It is a well-established process for large-scale industrial effluent treatment processes. Its application for on-site domestic sewage treatment started in 1988 in Cali, Columbia under the German Development Cooperation GTZ-biogas advisory service. The treatment efficiency achievable is 55-90% BOD removal. Biogas is always captured.

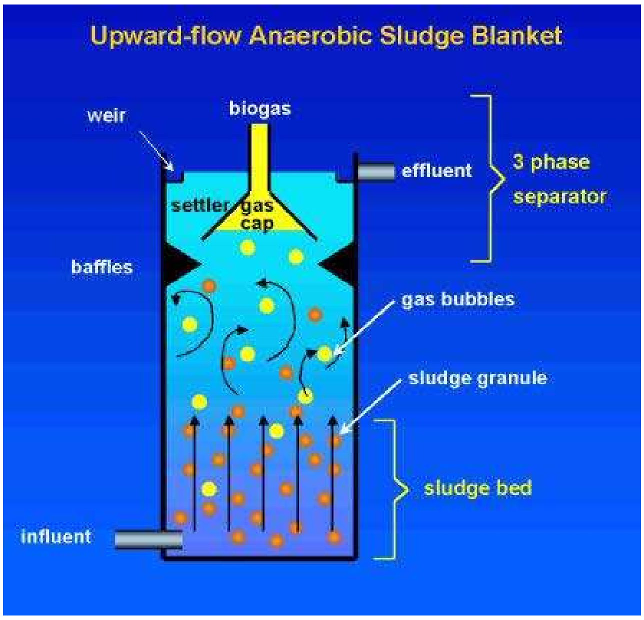

Figure 15: UASB design (source: http://www.uasb.org 2004)

5 Maintenance requirements for biogas sanitation systems

In difference to daily operation and control services, maintenance services should be carried out by well-trained biogas technician. One has to bear in mind that measurement indicating problems may be wrong. All doubtful measurements have to be verified. Often, one symptom has a variety of possible reasons. Maintenance is restricted to occasional inspections and where necessary – repairss to pipes and fittings. The entire installation itself – if operated and designed properly – needs little maintenance.

As the system works purely biologically, so NO chemicals, NO condoms, NO plastics or metal, NO sanitary pads, tampon or nappies should be disposed into toilets or any basin. NO colouring toilet liquid put into the toilet cistern. Do not tip any oil or chemicals into the toilet or the basin! Everything tipped in the toilet or basin influence the recycled water and the growing of the vegetables. That stuff might clog or kill the biological process.

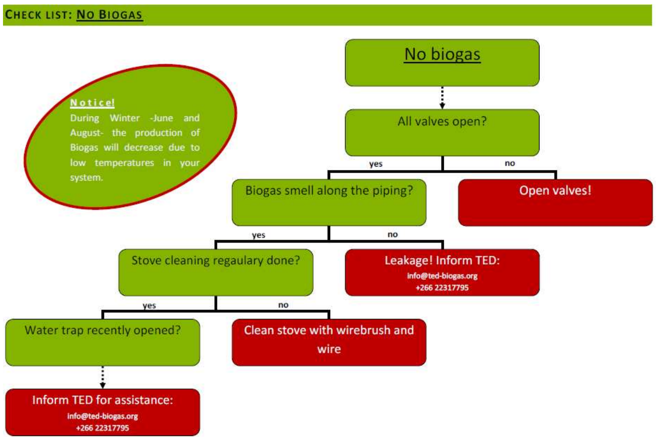

Figure 16: Maintenance checklist (extract) for biogas-sanitation systems (source: TED-Lesotho)

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Further information sources

Case studies of the Sustainable Sanitation Alliance (SuSanA) about biogas sanitation: http://www.susana.org/lang-en/case-studies/technology/biogas

Photos on flickr: http://www.flickr.com/photos/gtzecosan/sets/72157623382874630/

Video clips on youtube with keywords: biogas, sanitation.

Publications collated by the **SuSanA working group** on "sustainable sanitation and renewable energies" (note this group is open for all interested people to join): http://www.susana.org/lang-en/working-groups/wg03

Technical drawings collected on the website of SuSanA: http://www.susana.org/lang-en/cap-dev/technical-drawings/biogasplant

Figure 17: Promotional material for biogas systems, including biogas sanitation (source A. Krieg and H.-P. Mang)

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