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Anaerobic Digestion of Biowaste in Developing Countries

Practical Information and Case Studies

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Glossary

Acidogenesis: The second stage of the conversion of large organic molecules to volatile fatty acids.

Aerobic treatment: Degradation and stabilisation of organic compounds by microorganisms in the presence of oxygen.

Anaerobic Digestion (AD): Degradation and stabilisation of organic compounds by microorganisms in the absence of molecular oxygen (bio-methanisation) leading to production of biogas. This term is also used to describe the whole anaerobic treatment process.

Batch-feed: A process by which a reactor is filled with feedstock in one sequence, then processed and finally emptied in one instance. This is in contrast to continuous feeding.

Biodegradable: Material that can be broken down into basic molecules (e.g. carbon dioxide, water) by organic processes carried out by bacteria, fungi, and other microorganisms.

Biogas: A mixture of gases, predominantly methane and carbon dioxide, produced by the process of anaerobic digestion.

Carbon dioxide: A colourless, odourless, non-flammable gas and one of the two main constituents of biogas; chemical formula CO_2.

Degradation: A particular type of gradual decomposition of organic matter that usually proceeds in well-defined stages resulting in products with fewer carbon atoms than the original material. The term is often applied to decomposition by microorganisms.

Digestate: The solid and/or liquid material remaining after undergoing anaerobic digestion; often still high in nutrient content *(see effluent)*.

Digester: An enclosed tank, cylinder or silo in which anaerobic digestion of organic wastes takes place. In this book, the term reactor is used as synonym for digester.

Domestic waste: *See household waste.*

Effluent: The liquid that remains after a treatment or separation process; it refers to liquid which has gone through some type of clarification, settling, or biological process, flowing out of the digester.

Feedstock: Organic input material for subsequent treatment by aerobic or anaerobic processes. This material may vary in terms of particle size, moisture content (solid and/or liquid wastes) and ease of degradability.

Gasholder: A separate structure that receives and stores biogas produced in a digester. The digester and the gasholder are part of the AD system.

Household waste (domestic waste): Municipal solid waste composed of garbage and rubbish, which is generated as the consequence of household activities. In developing countries, up to two thirds of such waste consists of biodegradable material.

Hydraulic Retention Time (HRT): Defines the (average) amount of time that liquid and soluble compounds stay in a reactor. It has the unit of time and is calculated by dividing the volume of the reactor by the flow.

Hydrogen sulphide: A colourless, odorous and corrosive gas which is found as a minor constituent of biogas; chemical formula H_2S.

Inorganic matter: Material, such as grit, inorganic salts, metals, glass etc., which is not degraded by microorganisms.

Mesophilic: Microbial processes that take place in the moderate temperature range of 20–45°.

Methane: A colourless, odourless, flammable, gaseous hydrocarbon present in natural gas and formed by the anaerobic decomposition of organic matter; chemical formula CH_4.

Methanogenesis: The final conversion stage of acetic acid and hydrogen into biogas.

Municipal Solid Waste (MSW): Wastes generated by settlements, which includes households, commercial and industrials premises, institutions (schools, health care centres, prisons, etc.), and public spaces (streets, bus stops, parks and gardens).

Organic Fraction Of Municipal Solid Waste (OFMSW): The biodegradable fraction of municipal solid waste, also called biowaste.

Organic Loading Rate (OLR): The substrate quantity fed into the reactor volume in a given time. The unit is kg substrate (VS)/m^3 reactor and day.

Organic matter: Material from animal and vegetable sources which can be degraded by microorganisms.

pH: Measured as concentration of hydrogen ions in a solution and used as an indicator of acidity (pH<7) or alkalinity (pH>7).

Post-treatment: Treatment of the outputs from the anaerobic digestion process (effluent/digestate and/or gas) to further remove pollutants or pathogens.

Pre-treatment: Treatment of feedstock before filling into the digester (size reduction, sorting, etc.).

Slurry: A semi-liquid mixture of organic material, microorganisms and water *(see effluent).*

Solids Retention Time (SRT): The average length of time solid material remains in a reactor. SRT and HRT are equal for complete mix and plug flow reactors. Some two-stage reactor concepts decouple HRT from the SRT allowing the solids to have longer contact time with microbes while maintaining smaller reactor volume and higher throughput.

Stabilisation: The degradation of organic substances by aerobic and/or anaerobic microbial populations to yield biochemically stable products.

Thermophilic: Microbial activity at a relatively high temperature, in the range of 50–65 °C.

Total Solids (TS): When a water or sludge sample is filtered and dried at 105 °C, the residue that remains is referred to as the Total Solids. It is measured in mg/L (mass per volume) or as a percentage of wet weight. Moisture content plus TS (both expressed as percentage of wet weight) equal 100 per cent.

Volatile Solids (VS): The organic matter in a sample, usually expressed as a percentage of the Total Solids.

Rationale

Inadequate solid waste management (SWM) in urban centres of low- and middle-income countries is a serious environmental and health problem. Rapid urban population growth and the continual increase in waste generation intensifies the challenge. Often more than 50 % of the waste produced is organic and biodegradable. Therefore suitable treatment options for the organic fraction could help alleviate the waste problem. At the same time the worldwide drive to find clean, renewable energy sources remains a main priority. At national level, countries are keen to cut their reliance on fossil fuels due to concerns over security of supply and to provide alternatives to wood fuel, the main energy source for cooking and heating which is causing severe deforestation. At city level, residents, commerce and industries want to reduce their dependency on unpredictable price fluctuations of fuels. Finally, from a waste management and environmental impact perspective, national and local governments are committed to the issue of global warming and providing measures to avoid methane emissions from landfills.

Anaerobic digestion of organic waste, leading to the generation of biogas, provides a unique opportunity to fulfil all these objectives. There is no need for purpose-grown crops for fuel as organic waste supply is abundant. This approach contributes to improved waste management practices and at the same time fulfils the goals of sustainable energy management. Using waste biomass to produce biogas creates a carbon neutral cycle, in which the carbon emitted from burning the gas is absorbed by new crops from which the waste residues can be used again as feedstock. Biogas waste treatment facilities reduce the amount of waste disposed in uncontrolled dumping sites, which if unmanaged, release pollutants into air, water and soil, endangering the environment and contributing to greenhouse gas emissions. Digestate from biogas facilities is a valuable fertiliser for farmers and is particularly useful in countries where soil quality has become degraded through over-intensive farming. All countries throw away large volumes of organic waste, so all can benefit. All these arguments support the use of biogas as a global growth energy of the future and an appropriate waste treatment option.

How can this book help?

Research on anaerobic digestion solutions for low- and middle-income countries has shown that there is a wealth of knowledge and experience with small- and medium-scale digesters built in rural areas where manure from a few cattle and some household waste is used as feedstock. However, anaerobic digestion still seems to play a negligible role as a treatment option in urban settings for organic yard, kitchen or market waste. The use of this technology has recently become popular on a medium- and large-scale in industrialised countries, often using sophisticated technology with automated and mechanised control systems. However, transferring this rather advanced technology to a low-income country without consideration of local conditions and without specific adaptations will be predisposed to failure.

This book therefore aims to compile existing and recently generated knowledge on issues of anaerobic digestion of organic solid waste at small- and medium-scale with special consideration of low- and middle-income country conditions. The book is divided into two parts; Part 1 focussing on practical information related to anaerobic digestion and biogas production, and Part 2 presenting selected case studies from around the world.

Part 1 starts with a description of the substrate (feedstock) requirements (chapter 2), followed by an overview of digester types and the transformation processes of waste into valuable end products (chapter 3). It then continues with a discussion of the products derived from anaerobic digestion and the associated post-treatment, distribution and utilisation opportunities (chapter 4 and 5). The first part of the book ends with a chapter on sustainability aspects (chapter 6) discussing enabling and hindering factors which influence the success or failure of any biogas project and facility. The case studies presented in Part 2 aim to highlight the successes and lessons learnt from countries in which these technologies are applied.

It is important to highlight that the focus of this book is on anaerobic digestion of organic solid waste. Although some observed and documented technologies may also contain feedstock such as animal waste, human waste or wastewater, special emphasis has been placed on the challenges and opportunities of using organic solid waste.

An overview of the technologies that are currently being used in low- and middle-income settings is provided together with a description of the pros and cons of each technology. Case studies are used to illustrate the reality of experiences in practice. It is not the aim of this book to convince the reader that anaerobic digestion is more suitable than any other organic waste treatment technology, such as composting, briquetting or animal feeding. The decision as to which treatment approach is most practicable and sustainable depends on many site-specific factors which vary depending on the country, region and city of concern. Therefore, the objective of this book is to ensure that decision makers have access to unbiased information, with which they can identify the local conditions that need to be considered, before deciding if anaerobic digestion might be an appropriate solution.

The content of this book will not satisfy an academic audience in search of textbook knowledge on fundamental principles of anaerobic treatment processes; here it is recommended that Mata-Alvarez (2003) or Palmisano & Barlaz (1996) be consulted.

Target audience

This book is considered relevant to a wide range of individuals and organizations working in the waste and renewable energy sector. It provides insight to entrepreneurs and private investors intending to fund, set up or manage a biogas plant; local authorities wanting to invest in or operate organic waste digestion plants as one element of their solid waste management master plan; contractors managing biogas plants; and staff of international and national donor and non-governmental organizations funding and supporting biogas projects. No prior understanding of anaerobic digestion is necessary; however a basic background in natural science (biology, chemistry) may be helpful for a better understanding of the details.

Sources of information

The authors have drawn heavily on literature and reports but combined this with information from their own research and observations, and from an analysis of case studies from low- and middle-income countries. All consulted literature is referenced in the text and listed in the literature section.

PART I: PRACTICAL INFORMATION

1. Introduction

1.1. Anaerobic digestion at a glance

Anaerobic digestion (AD) is a microbiological process whereby organic matter is decomposed in the absence of oxygen. This process is common to many natural environments such as swamps or stomachs of ruminants. Using an engineered approach and controlled design, the AD process is applied to process organic biodegradable matter in airproof reactor tanks, commonly named digesters, to produce biogas. Various groups of microorganisms are involved in the anaerobic degradation process which generates two main products: energy-rich biogas and a nutritious digestate.

Benefits of biogas technologies

Anaerobic digestion of organic waste provides many benefits. This includes the generation of renewable energy, a reduction of greenhouse gases, a reduced dependency on fossil fuels, job creation, and closing of the nutrient cycle. It transforms organic waste material into valuable resources while at the same time reducing solid waste volumes and thus waste disposal costs. Biogas as a renewable energy source not only improves the energy balance of a country but also contributes to the preservation of the natural resources by reducing deforestation, and to environmental protection by reducing pollution from waste and use of fossil fuels (Al Seadi et al., 2008).

Aerobic or anaerobic?

Aerobic degradation takes place in the presence of oxygen. Since aerobic degradation occurs much faster than anaerobic digestion, aerobic processes are prevalent and dominant when free oxygen is available. The rapid rate of decomposition is caused by the shorter reproduction cycles of aerobic bacteria as compared to anaerobic microorganisms. The latter leave some of the energy unused, which is released in the form of biogas.

The anaerobic process is not as efficient as the aerobic process in breaking down waste products. Without free oxygen, bacteria cannot derive as much energy from the breakdown of food molecules as bacteria using oxygen. For instance, in a well aerated compost pile, there is rapid breakdown of the organic materials. With the energy released by microbial processes, the temperature inside a compost pile often reaches 70 °C during its most active period. Similar material placed in a biogas reactor (i.e. in an environment without oxygen) produces no appreciable heat, decomposes rather slowly, and most of the energy remains locked up in the form of methane. This difference between aerobic and anaerobic metabolism with regards to efficient use of energy is also evident by the stability of the process. Anaerobic digestion generation is easier to disturb than the process inside a compost pile. Changes in surrounding conditions, feedstock, or levels of toxic inhibiting substances can easily disrupt or stop the anaerobic process (House, 2010) whereas it would hardly affect the composting process.

Calorific value of biogas

The calorific value of biogas is around 6.0–6.5 kWh/m³, depending on the percentage of methane present, which on average is in the range of 55–70 Volume-% (Deublein and Steinhauser, 2011). The net calorific value depends on the efficiency of the biogas burners or other appliances used to process the biogas. A gas generator, for example, can convert about 2 kWh into useable electricity, while the remaining energy is emitted as heat.

Table 1 shows examples of calorific value of different fuel sources as compared to biogas as well as the approximate mass of that fuel corresponding to 1 m³ of biogas.

Fuel Source	Approximate Calorific Value	Equivalent to 1 m³ Biogas (approx. 6 kWh/m³)
Biogas	6–6.5 kWh/m³	
Diesel, Kerosene	12 kWh/kg	0.50 kg
Wood	4.5 kWh/kg	1.30 kg
Cow dung	5 kWh/kg dry matter	1.20 kg
Plant residues	4.5 kWh/kg dry matter	1.30 kg
Hard coal	8.5 kWh/kg	0.70 kg
Propane	25 kWh/m³	0.24 m³
Natural gas	10.6 kWh/m³	0.60 m³
Liquefied petroleum gas	26.1 kWh/m³	0.20 m³

Table 1: Calorific value of different fuels [1].

Rule of thumb

Roughly 10 kg (wet weight) of biowaste (e.g. kitchen and market waste) are needed to produce 1 m³ of biogas. This amount of biogas contains approximately 6 kWh (or 21.6 MJ) of energy.

1.2. Development of anaerobic digestion in developing countries

The process of anaerobic digestion has been practised for decades in developing countries. Reports describe an early anaerobic digester in Mumbai, India, built in 1859 for sewage treatment. Since then, the technology has become widespread throughout Asia. Different biogas support programmes focus on rural families with a few cattle where animal manure and human faeces are used as feedstock together with the addition of small amounts of kitchen waste. The development drivers for introducing such systems to provide people with biogas, is to reduce consumption of firewood and the respective deforestation, decrease indoor air pollution and improve soil fertility.

After roughly 25 years of step-wise improvements and practical experience, the technology is still attracting interest as a contribution to renewable energy production and creating independence from fossil fuels. The Ministry of Agriculture, China, added an estimated 22 million biogas systems between 2006 and 2010 to reach a total of some 40 million installed systems in early 2011. India is home to approximately 4 million systems, and Vietnam has installed 20 000 systems annually to reach more than 100 000 by 2010. Cambodia, Laos, and Indonesia have smaller biogas programmes, nevertheless installing about 1 000 systems in each country in 2010. Nepal's Biogas Support Programme, which involves the private sector, microfinance organizations, community groups, and NGOs, has resulted in a steady increase in installed biogas systems during the last decade. Approximately 25 000 systems were constructed in 2010, bringing the nationwide total to nearly 225 000 (REN21, 2011).

In Africa, where anaerobic digestion is less prevalent, a biogas support programme was launched in May 2007. Based on the experience in Asia, the African "Biogas for Better Life" initiative aims at installing two million biogas plants in rural households by 2020 (Nes and Nhete, 2007). In Latin America, apart from small biogas plants for rural households, numerous agricultural waste projects have been implemented and in the urban environment biogas is being extracted from several landfills (landfill gas).

While anaerobic digestion of organic household waste in centralised high-technology plants in industrialised countries has become increasingly popular in recent years, most regions of developing countries still lack appropriate low-technology options. As a result, anaerobic digestion as a waste treatment option for urban settings, predominantly processing kitchen or market waste, still plays a negligible role. There is little knowledge and information available or accessible on technical and operational feasibility, challenges and opportunities. Based on literature research, experience and development, India appears most prominent with regard to AD processing of organic waste (Vögeli and Zurbrügg, 2008). This may also be due to the fact that Chinese literature is seldom published in English and thus remains inaccessible to many researchers and practitioners worldwide.

1.3. Process chain of anaerobic digestion of biowaste

This book structures the information on the anaerobic digestion processes and elements based on a systemic supply chain perspective as shown in Figure 1. The following three main components are addressed in detail in subsequent chapters:

- **Substrate chain:** Waste generation, collection, transportation and supply to the digestion facility, and necessary pre-treatment of waste before feeding the digester (chapter 2).
- **Transformation process:** Biological and chemical transformation processes of feedstock in the digester which leads to value products (chapter 3).
- **Product chain:** Post-treatment of outflows from the digester that refine these into improved value products, and their distribution and utilisation (chapter 4 and 5).

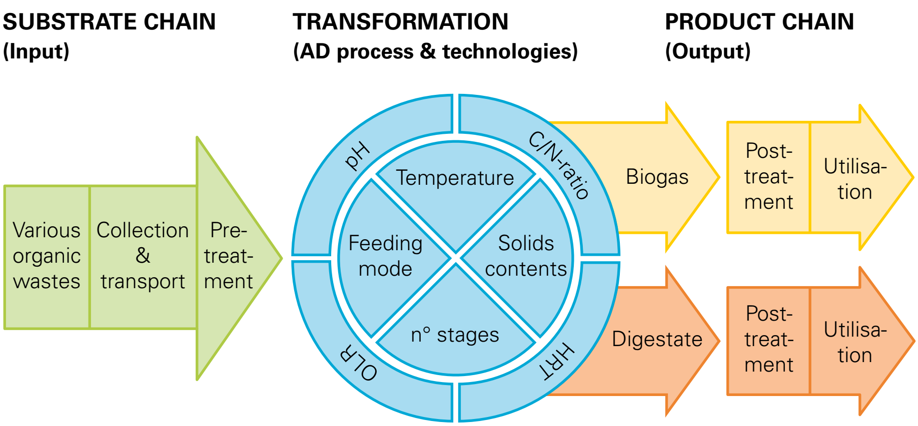


Figure 1: Process chain of anaerobic digestion.

2. Substrate Chain

2.1. Feedstock sources

Biomass suitable for digestion is called "substrate" or "feedstock". The organic wastes that can be treated by anaerobic digestion cover a wide spectrum. Historically anaerobic digestion has been used to treat liquid wastes, with or without suspended solids, such as manure, sewage, industrial wastewater and sludge from biological or physical-chemical treatment. Using solid wastes such as agricultural and municipal solid waste only started to attract attention in the anaerobic digestion sector during the sixties due to its high organic matter content and therefore high potential for biogas production (Mata-Alvarez, 2003).

Table 2 provides an overview of the various feedstocks from municipal, agricultural and industrial sources. From a municipal source, human excreta is also a potential substrate for biogas production. However, compared to biowaste it has a lower biogas yield, as the initial feedstock has already been digested once and the energy has been extracted. Furthermore in some cultures (e.g. particularly Muslim countries) the handling of excreta and use of products from human waste (gas, digestate) faces cultural and religious taboos (Kossmann et al., undated). Lignin, one of the main wood constituents, cannot be degraded under anaerobic conditions (Mata-Alvarez, 2003).

Municipal	Agriculture	Industry
• Organic fraction of municipal solid waste ("biowaste") • Human excreta	• Manure • Energy crops • Algal biomass • Agro-industrial waste	• Slaughterhouse waste • Food processing waste • Biochemical waste • Pulp and paper waste

Table 2: Various feedstock from different sources.

Degradability of different substrates

Of the total dry matter content - typically referred to as Total Solids (TS) - only the organic biodegradable fraction contributes to biogas production (Figure 2). This organic dry matter is also called "Volatile Solids" (VS), which is the parameter commonly used to characterise the organic waste for anaerobic digestion. In general, the organic dry matter content of suitable biowaste substrates range from 70 % to more than 95 % of the TS. Substrates with less than 60 % organic dry matter content are rarely considered as valuable substrates for anaerobic digestion.

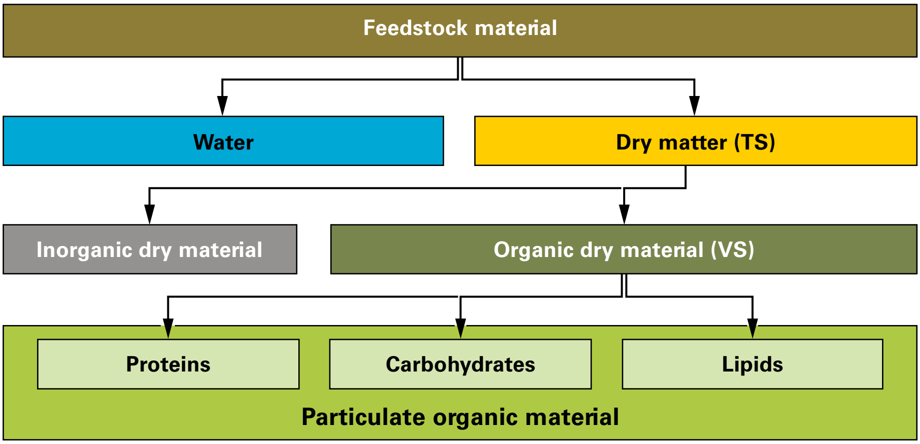


Figure 2: Classification of feedstock material (adapted from Müller, 2007).

Table 3 lists the percentage of TS and VS from different substrate sources as presented in literature. As is evident, there is some diverging information on TS and VS content despite identical naming (e.g. market waste). This is most likely due to the differences in specific waste composition.

Substrate	TS (% of raw waste)	VS (% of TS)	Literature Source
Spent fruits	25–45	90–95	Deublein and Steinhauser (2011)
Vegetable wastes	5–20	76–90	Deublein and Steinhauser (2011)
Market wastes	8–20	75–90	Deublein and Steinhauser (2011)
Leftovers (canteen)	9–37	75–98	Deublein and Steinhauser (2011)
Overstored food	14–18	81–97	Deublein and Steinhauser (2011)
Fruit wastes	15–20	75–85	Gunaseelan (2004)
Biowaste	25–40	50–70	Eder and Schulz (2007)
Kitchen waste	9–37	50–70	Eder and Schulz (2007)
Market waste	28–45	50–80	Eder and Schulz (2007)

Table 3: Total Solids (TS) and Volatile Solids (VS) in biowaste.

Biogas yield

Biogas yield is affected by a number of factors such as type and composition of substrate, temperature, and mixing. The most common indicator of digester performance is the biological methane potential (BMP), which describes the maximum possible volume of methane gas that can be produced per unit mass of solid or volatile solid matter (Buffiere et al., 2006). Some methane yield values from anaerobic digestion of solid organic waste are shown in Table 4. The average methane yield of MSW is between 0.36 and 0.53 m^3/kg VS (Khalid et al. 2011).

Substrate	Methane Yield (L/kg VS)
Palm oil mill waste	610
Municipal solid waste	360–530
Fruit and vegetable wastes	420
Food waste	396
Rice straw	350
Household waste	350
Swine manure	337
Maize silage and straw	312
Food waste leachate	294
Lignin-rich organic waste	200

Table 4: Biogas yield recorded from anaerobic digestion of organic solid waste (Khalid et al., 2011).

It's important to note that the accuracy of gas measurements differ depending on the parameter used. In the list below the accuracy increases from top to bottom, i.e. the error rate increases from bottom to top (Eder and Schulz, 2007).

1. m^3 biogas/t substrate (wet weight)
2. m^3 biogas/kg Total Solids
3. m^3 biogas/kg Volatile Solids
4. m^3 CH_4/kg Volatile Solids
5. Nm^3 CH_4/kg Volatile Solids

Nm^3 stands for Norm m^3. As the volume of gases is dependent of temperature and pressure, the most precise description of the energy content in biogas is given under norm conditions (temperature 0 °C, pressure 1.01325 bar, relative gas humidity 0 %) in relation to the organic matter (VS) in the waste. It is therefore more precise to relate the gas production (most accurately in norm litres) to kg organic matter (Volatile Solids) than to kg dry matter (Total Solids) or even to kg substrate (wet weight).

2.2. Challenges of organic solid waste management

As this publication focuses on the organic fraction of municipal solid waste (OFMSW), or biowaste, the following chapters highlight the characteristics of this waste fraction and the considerations for collection, transport and pre-treatment when using biowaste as feedstock for anaerobic digestion.

In developing countries, the largest share of the municipal solid waste (MSW) consists of organics, and a relatively small amount of glass, metals and plastics (Figure 3). However, income level, economic growth, lifestyle, and location strongly influence MSW composition. Poor households typically generate less waste but higher fractions of organic waste than wealthy households. Rural and urban households show similar differences, with rural areas generating a high fraction of organic waste. Higher fractions of organics in household waste leads to a dense and rather humid waste that affects not only the collection and transport system but also its recycling potential (Eawag, 2008).

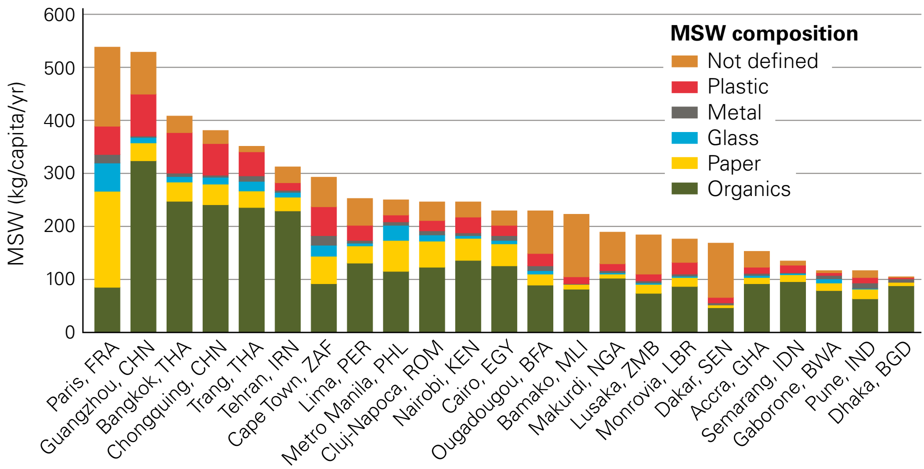


Figure 3: Composition of MSW (kg/capita/year) in 23 cities (Eawag, 2008).

The composition of municipal biowaste can change during the year given seasonal variations and habits (Li, Park and Zhu, 2011). During fasting season, for instance, or during special festivities when specific kinds of food are consumed, an increase of (bio)waste may be observed.

Organic waste recovery and recycling is still fairly limited. Next to direct animal feeding the most common practice for disposal of organic waste is dumping into unsanitary landfills or open dumpsites mixed with other waste streams. Recycling of organic waste would significantly reduce the amount of waste that needs handling and thus reduce costs at the disposal facilities. Less organic waste at the disposal site prolongs its life span, and also reduces the environmental impact of the disposal site as the organics are largely responsible for the polluting leachate, methane and odour problems. The implementation of anaerobic digestion or composting as one step in a city-wide solid waste management programme reduces the flow of biodegradable materials to landfills. Nevertheless its feasibility depends on the market demand for the end products (gas, digestate or compost), as well as the technical and organizational set-up of the individual facilities. An enabling clear legislation, policy and municipal strategy in terms of organic waste management are further important prerequisites for successful initiatives (Zurbrügg, 2003).

2.3. Collection and transport

The characteristics of the waste materials used for AD are highly dependent on the collection system (Hartmann, 2002), and one of the fundamental issues is whether the collected waste is contaminated by inorganic materials. If waste is being segregated at source and collected separately, the quality of this feedstock is increased, and the need for sorting at the AD plant reduced, thereby reducing infrastructure and human resources requirements. The box below highlights the differences between source segregation and sorting at the AD plant.

Source segregation
Actions taken at the point of waste generation to keep and store certain materials (in this case organics) separately from other waste (Scheinberg et al., 2010).

Sorting at the AD plant
The organic fraction is either manually or mechanically separated from the other waste streams as part of the pre-treatment process before being fed to the digester.

In most low- and middle-income countries separate collection of household segregated organic waste is rare. Thus the collected waste consists of organic waste mixed with other waste materials and any planned organic waste treatment will require subsequent sorting of the biowaste fraction. This not only leads to additional costs, but more importantly, results in lower quality biowaste feedstock. An exception to this is waste collected from sources which generate predominately biowaste with few contaminating inorganic substances, such as wastes from vegetable markets, restaurants or food processing industries. Biogas plants should therefore be built or located where large amounts of organic waste are accumulated.

Source segregated biowaste is generally of higher quality as it contains less non-degradable contaminants such as glass, plastic, rubber, stones, sand and hazardous and/or toxic substances. Such comparatively "pure" biowaste is thus ideal for treatment in an AD system. A manual sorting is nevertheless inevitable to ensure that impurities in the feedstock to an AD facility are removed, as this may lead to clogging of inlet pipes, reduced biogas yield and lower quality and acceptability of the digestate.

When the main objective of the treatment facility is to treat waste, with little priority of cost effectiveness or digestate quality, then collection of mixed waste and subsequent sorting before digestion may be suitable (Monnet, 2003). However, if the purpose of the AD facility is to produce high quality digestate, then the purity of the waste is very important and source segregated waste is preferred.

It is important to note that the storage time of collected biowaste should be as short as possible, especially in hot and humid climates. During storage, organic matter starts to decompose. Thus with longer storage biogas yield will decrease as waste has already degraded and lost some of its energy value. Furthermore, storage of biowaste goes hand in hand with proliferation of insects, rodents and other disease vectors and even emission of greenhouse gases. When storage is inevitable, one common practice is to attempt to stabilise biowaste by enhancing lactic acid fermentation (silage). Silage is made either by placing cut waste in a silo, by piling it in a large heap covered with plastic sheet, or by wrapping large bales in plastic film. Silage undergoes low–pH anaerobic fermentation, which starts about 48 hours after the silo is filled, and converts sugars to acids. In the past, the fermentation was conducted by indigenous microorganisms, but today, it is often inoculated with specific microorganisms to speed fermentation or improve the resulting silage. Silage inoculants contain one or more strains of lactic acid bacteria. Lactic acid fermentation leads to a low pH of 4–5 which prevents further anaerobic degradation to CO_2 and CH_4. The process is essentially complete after about two weeks, but can however be run stable for months. The total loss of organic material (not available for further biogas production) is in the range of 3–6 % and is frequently accompanied by a pre-hydrolysis of organics which can even lead to an overall slight increase of degradability and biogas production.

Picture 1: Handcart for collecting different waste fractions at source in Bangalore (photo: Sandec).

Picture 1 shows one example of neighbourhood waste collection by bicycle carts in Bangalore, India, which collect segregated biowaste from households. Residents are asked to keep "wet waste" (biowaste) in a separate bin. The waste collection cart has different containers to transport biowaste separate from "dry waste" which consist of all other non-degradable waste materials. A similar system for separate biowaste collection at the source of waste generation can also be observed at canteens or restaurants (Picture 2), and at markets for vegetable and fruit sellers (Picture 3). These are ideal settings and sources for AD feedstock.

Picture 2: Bucket for collection of food leftovers at a school in Tanzania: "Put only food waste" (photo: Sandec).

Picture 3: Separate collection of market waste in India (photo: Sandec).

2.4. Pre-treatment and feeding procedure

Most feedstocks require pre-treatment prior to digestion. Feedstock pre-treatment includes sorting (if not already done at source), reduction in particle size and addition of water before the mixture is fed into the AD system. Pre-treatment can enhance degradation of volatile solids and thus increase biogas yield (Tiehm et al., 2001). Some of the reasons why pre-treatment of incoming waste is needed and how it can be achieved are described in the following paragraphs (Deublein and Steinhauser, 2011).

Non-biodegradable material such as metals, plastic and glass can cause disturbances in the liquid flow, may clog pipes and can remain as noxious matter in the residue. Common procedures for removal of this material are manual separation, or magnetic separation for metals. An example of a sorting platform for the separation of wastes at a biogas plant is shown in Picture 4.

Picture 4: Sorting platform for incoming mixed waste at a municipal biogas plant in Mumbai (photo: Sandec).

The substrate should also be free of impurities like grit and sand as these will precipitate in the digester and reduce the volume available for treatment.

High amounts of fibrous material (e.g. straw) or clumps of material need to be avoided as this hinders the degradation process in the digester. Straw can cause considerable scum layer formation which is difficult to control during digestion. Breaking apart the clumps in a rotating drum and shredding is recommended.

Reducing the particle size of the feedstock is important to avoid blockage of the inlet pipe, and to increase ease of degradation. As a general rule, substrate particle size with a diameter of max. 5 cm are recommended although the ideal size also depends on the diameter of the inlet pipe. Shredding of the feedstock into small particles increases the total surface area of the material thus increasing the area that can be degraded by microorganisms (Schnürer and Jarvis, 2010), as many microorganisms, especially those that are active in the initial hydrolytic step, prefer to attach to the surface area of the material that they are degrading. Pictures 5 to 8 present different ways with which particle size can be reduced. These range from small equipment such as manual mincing machines suited for small amounts for household scale, to larger manual or power driven grinders for larger amounts at institutional scale. At the AD facility, particle size reduction can be energy and labour intensive depending on the equipment used.

In most wet digestion systems, the volume of feedstock added to the digester displaces the same volume of slurry/effluent from the digester to the outlet. This liquid outflow can also be mixed with the biowaste feedstock and fed back into the digester. Such an activity adds an appropriate bacterial population to the fresh biowaste and thus accelerates the start of the degradation process.

Picture 5: Manual mincing machine in Tanzania (photo: Sandec).

Picture 6: Manual mincing machine in Nepal (photo: Sandec).

Picture 7: Mincing machine in India (photo: Sandec).

Picture 8: Electrical blender with water connection in India (photo: Sandec).

Suitable feedstock loading of digesters is crucial to avoid problems with digestion (see also chapter 3.2). Dilution of biowaste with water helps control the total TS fed to the digester. Feeding too much TS can lead to clogging of pipes. Too little TS (i.e. too much dilution with water) will decrease potential gas yield or, where the digester needs heating (e.g. in cold climates) it will increase energy requirements for the heater.

In a continuous system, the digester must be fed regularly in order to ensure a more or less constant gas production. Small size biogas plants can be fed manually; for larger digesters pipes or channels, belts or pumps are typically used.

3. Anaerobic Digestion Process, Technology and Operation

3.1 Biochemical process of anaerobic digestion

Anaerobic digestion (AD), also referred to as biomethanation or biomethanisation, is the biochemical decomposition of complex organic material by various bacterial activities in the absence of oxygen. The two main products of AD are biogas, and a mixture of bacterial biomass and inert organics, often referred to as digestate or effluent.

The anaerobic decomposition of organic matter occurs in a four-step process as presented in Figure 4 and described in the following sections.

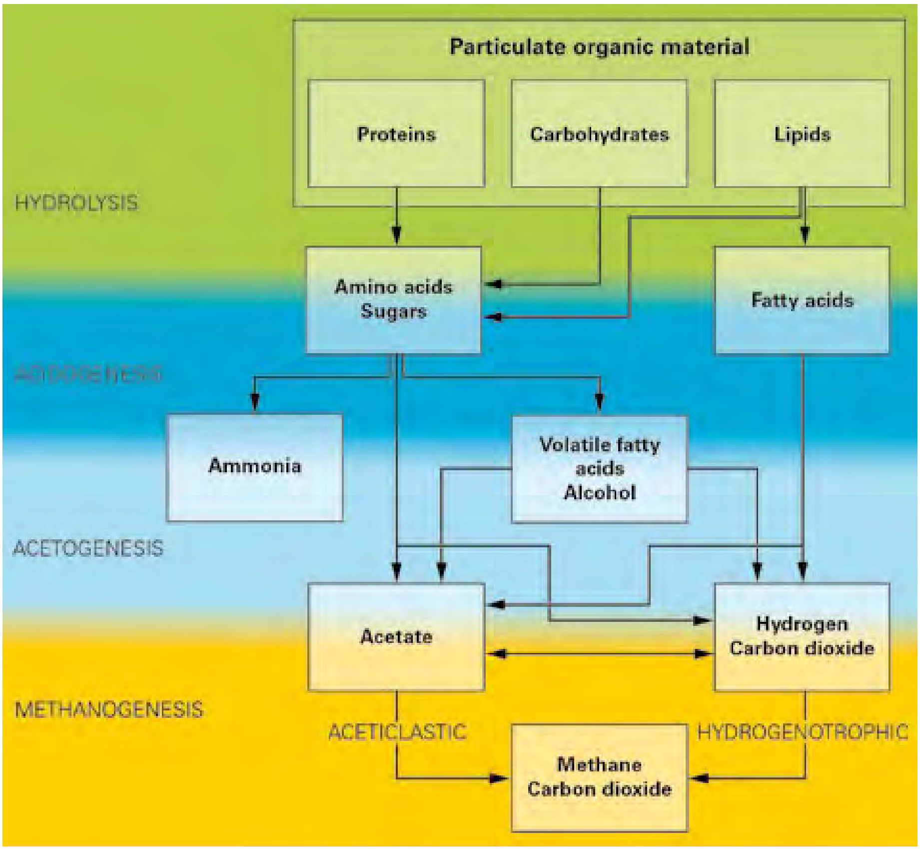


Figure 4: Schematic biodegradation steps of complex organic matter (adapted from Mata-Alvarez, 2003).

Hydrolysis

This first stage is usually the slowest of the four degradation steps. The bacteria transform complex organic materials into liquefied monomers and polymers; i.e. proteins, carbohydrates and lipids (fats) are transformed to amino acids, monosaccharides and fatty acids respectively (Arnell et al., 2007; Murphy and Polaficio, 2007). This extracellular enzyme-mediated transformation of higher mass organic molecules into basic structural building blocks is very important as particulate organic materials are simply too large to be directly absorbed and used by microorganisms as substrate/food source.

Acidogenesis

In the second stage, acidogenic bacteria convert the soluble organic monomers of sugars and amino acids to ethanol and acids (such as propionic and butyric acid), acetate, H_2 and CO_2. The degradation of amino acids also leads to production of ammonia.

Acetogenesis

In this third stage both long chain fatty acids and volatile fatty acids and alcohols are transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. During this reaction the BOD (biological oxygen demand) and the COD (chemical oxygen demand) are both reduced and the pH decreased (Bischofsberger et al., 2005; Bekker, 2007). Hydrogen plays an important intermediary role in this process, as the reaction will only occur if the partial pressure is low enough to thermodynamically allow the conversion of all the acids. Hydrogen scavenging bacteria lead to a lower partial pressure. Thus the hydrogen concentration in a digester is an indicator of its "health" (Mata-Alvarez, 2003).

Methanogenesis

During this final stage, methanogenic bacteria convert the hydrogen and acetic acid to methane gas and carbon dioxide. Methanogenesis is affected by conditions in the reactor such as temperature, feed composition and organic loading rate (Parawira, 2004).

The gaseous product, biogas, consists mainly of methane (CH_4) and carbon dioxide (CO_2), but also contains several other gaseous "impurities" such as hydrogen sulphide (easily detectable by its smell of rotten eggs), nitrogen, oxygen and hydrogen (see Table 5). Biogas with a methane content higher than 45 % is flammable; the higher the CH_4 content the higher the energy value of the gas (Deublein and Steinhauser, 2011).

Components	Symbol	Concentration (Vol-%)
Methane	CH_4	55–70
Carbon dioxide	CO_2	35–40
Water	H_2O	2 (20 °C) – 7 (40 °C)
Hydrogen sulphide	H_2S	20–20 000 ppm (2 %)
Nitrogen	N_2	< 2
Oxygen	O_2	< 2
Hydrogen	H_2	< 1
Ammonia	NH_3	< 0.05

Table 5: Typical composition of biogas from biowaste (adapted from Cecchi et al., 2003).

The rate and efficiency of the anaerobic process is affected by the waste type and the operational parameters as described in the following section.

3.2 Operational parameters

The rate at which the microorganisms grow is of paramount importance for the AD process. The operating parameters of the digester are therefore controlled so as to enhance the microbial activity and thus increase the AD efficiency. The most important parameters are described below.

Temperature

While AD technology is principally feasible under almost all climatic conditions, at low temperatures (mean temperature below 15 °C) the digestion process does not work satisfactorily (Kossmann et al., undated). In cool climatic conditions either a heating system has to be installed or a larger digester has to be built in order to increase retention time (Buysman, 2009). Heating systems and insulation can provide optimal digestion temperatures even in cold climates or seasons, however the required additional investment costs and fuel costs for heating may render the biogas system economically unviable. Not only is the mean temperature an important parameter for the AD process but large temperature variations, such as those between day and night, or seasonal variations, can also adversely affect the performance of an AD system. Digesters built underground help to minimise these changes by using the temperature buffer capacity of the soil. For household digesters the design should ensure that gas production remains sufficient even during the most unfavourable season of the year. Given the additional investments required in colder climates, a general rule is that the costs of biogas production increase as the temperature decreases.

There are two ideal temperature ranges for the performance of anaerobic bacteria; one at 30–40 °C for mesophilic microorganisms (optimum temperature 37 °C) and one at

45–60 °C for thermophilic microorganisms (optimum temperature 55 °C) (Mata-Alvarez, 2003). Operation of a digester in the mesophilic range is more stable, as these microbial communities can tolerate greater changes in environmental parameters and consume less energy. Inhibition by ammonium is less critical in the mesophilic range as compared to thermophilic conditions due to the lower content of free ammonia at lower temperatures. On the down side however, the mesophilic microorganisms are slower and thus a longer retention time in the digester is needed to maximise biogas yield. The thermophilic mode of digester operation results in approximately 50 % higher rate of degradation and, particularly with fat-containing materials, a better availability of the substrates to the enzymes excreted by the acidogens and thus a higher biogas yield (Deublein and Steinhauser, 2011). Due to the lower solubility of CO_2 at higher temperatures a 2–4 % higher CO_2 concentration in biogas can be observed in thermophilic digesters. Despite some advantages of AD at higher temperatures, operating the digester at thermophilic ranges is generally considered less feasible in a developing country context due to the additional energy inputs required as well as the lower stability of the process.

pH

The optimum pH for a generally stable AD process and high biogas yield lies in the range of 6.5–7.5 (Mata-Alvarez, 2003; Khalid et al., 2011). During digestion, the processes of hydrolysis and acidogenesis occur at acidic pH levels (pH 5.5–6.5) as compared to the methanogenic phase (pH 6.5–8.2) (Khalid et al., 2011). An alkalinity level of approximately 3 000 mg/L has to be available at all times to maintain sufficient buffering capacity. Lime is commonly used to raise the pH of AD systems when the process is too acidic. Alternatively, sodium bicarbonate can also be used for pH adjustment (Igoni et al., 2007). Lime is usually much cheaper and there might be free sources of spent lime solutions from local industry. Lime however frequently leads to precipitations and clogging of pipes when used in larger quantities. Sodium bicarbonate and sodium hydroxide are fully soluble and usually do not lead to precipitations, but on the other hand they contribute to higher costs. Additionally, the availability of sodium bicarbonate or sodium hydroxide is sometimes lower than lime. For immediate action, the addition of sodium salts is recommended. For back-up pH-adjustment of low pH substrates, lime might be the choice.

Carbon to nitrogen ratio

The relationship between the amount of carbon and nitrogen in organic materials is represented by the C:N ratio. The C:N ratio is an important parameter in estimating nutrient deficiency and ammonia inhibition (Hartmann, 2002). Optimal C:N ratios in anaerobic digesters are between 16 and 25 (Deublein and Steinhauser, 2011). A high C:N ratio is an indication of rapid consumption of nitrogen by methanogens, which then results in lower gas production. On the other hand, a low C:N ratio causes ammonia accumulation and pH values then may exceed 8.5. Such conditions can be toxic to methanogenic bacteria (Verma, 2002). Although methanogenic bacteria can adapt to very high ammonia concentrations this only happens if concentrations are increased gradually allowing time for adaptation. Optimum C:N ratios can be ensured by mixing different feedstock materials, with high (e.g. organic solid waste) and low (e.g. sewage or animal manure) C:N ratios to achieve an ideal C:N ratio level.

Inoculation and start-up

When starting the digester for the first time, the digester needs to be inoculated with bacteria necessary for the anaerobic process. Diluted cow dung (optimally 1:1 ratio with water) is an ideal inoculate. Typically, the minimum cow dung required for good inoculation amounts to 10 % of the total active reactor volume. In general, the more cow dung used for inoculation, the better. During the start-up phase, the bacteria population needs to be gradually acclimatized to the feedstock. This can be achieved by progressively increasing the daily feeding load which allows time to achieve a balanced microorganism population. Initial overloading presents a risk to the overall anaerobic process. Overloading results from either feeding too much biodegradable organic matter compared to the active population capable of digesting it, or rapidly changing digesters conditions (e.g. abrupt change of temperature, accumulation of toxic substances, flow rate increase). Such disturbances specifically affect methanogenic bacteria, whereas the acidogenic bacteria, which are more tolerant, continue to work, and produce acids. This eventually leads to an acidification of the digester which inhibits the activity of methanogens. Such an imbalance of acidogenic versus methanogenic bacteria can result in digester failure. Addition of manure can avoid this as it increases the buffer capacity, thereby reducing the risk of acidification.

The gas that is produced in the first weeks after start-up is mainly carbon dioxide (CO_2). This gas is not flammable and can be released. After a few days the methane content of the gas will have sufficiently increased to a level that can sustain a flame ($CH_4 > 45$ Vol.-%) and lead to high quality biogas (55 – 70 Vol.-%).

Organic Loading Rate

The Organic Loading Rate (OLR) is a measure of the biological conversion capacity of the AD system. It represents the substrate quantity introduced into the reactor volume in a given time (see Table 6). OLR is a particularly important control parameter in continuous systems, as overloading leads to a significant rise in volatile fatty acids which can result in acidification and system failure as described above. Studies of anaerobic treatment of biowaste in industrialized countries describe organic loading rates in the range of 4 – 8 kg VS/m^3 reactor and day, which result in VS removal in the range of 50 – 70 % (Vandevivere et al., 2003). This is ideal for continuously stirred reactors. However, for non-stirred AD systems which are predominant in developing countries, an OLR below 2 kg VS/m^3 reactor and day is recommended and considered suitable.

Hydraulic Retention Time

The Hydraulic Retention Time (HRT) quantifies the time the liquid fraction remains in the reactor. It is calculated by the ratio of the reactor (active slurry) volume to the input flow rate of feedstock (see Table 6). The HRT required to allow complete AD reactions varies with different technologies, process temperature and waste composition. Recommended HRT for wastes treated in a mesophilic digester range from 10 to 40 days. Lower retention times down to a few days only, are required in digesters operated in the thermophilic range (Verma, 2002). A distinction is made between Hydraulic Retention Time (HRT) and Solids Retention Time (SRT), but for digestion of solid waste, HRT and SRT are generally considered equal.

Operational Parameter	Formula	Description	Unit
Hydraulic Retention Time (HRT)	HRT = V/Q	HRT: Hydraulic retention time V: Reactor volume Q: Flow rate	days m^3 m^3/day
Organic Loading Rate (OLR)	OLR = Q*S/V	OLR: Organic loading rate Q: Substrate flow rate S: Substrate concentration in the inflow V: Reactor volume	kg substrate (VS)/m^3 reactor and day m^3/day kg VS/m^3 m^3
Gas Production Rate (GPR)	GPR = Q_{biogas}/V	GPR: Gas production rate Q_{biogas}: Biogas flow rate V: Reactor volume	m^3 biogas/m^3 reactor and day m^3/day m^3
Specific Gas Production (SGP)	Q_{biogas}/Q*S or GRP/OLR	SPG: Specific gas production Q_{biogas}: Biogas flow rate Q: Inlet flow rate S: Substrate concentration in the inflow	m^3 biogas/kg VS fed material m^3/day m^3/day kg VS/m^3

Table 6: Main parameters for evaluation and comparison of different AD system performances (Mata-Alvarez, 2003).

Mixing

The purpose of mixing and stirring inside the digester is to blend the fresh material with digestate and thus inoculate the fresh material with microbes. Such mixing avoids temperature gradients within the digester and also prevents scum formation. Scum and foam is a result of filamentous microorganisms in the digester. Low concentrations of substrate in AD plants lead to an increase in the growth of filamentous bacteria compared to flocculating bacteria. Scum in digesters should be avoided as it can result in blockage of the gas pipe or potentially lead to a foaming over of the digester. This results in displacement of slurry into pipes, machines and devices resulting in subsequent malfunction or corrosion. Loss of bacteria is usually a minor problem as they regrow. A constant top layer of 20 – 60 cm of foam is usually regarded as "stable" in large-scale systems and is acceptable or easy to manage. A thicker impermeable scum layer however may prevent gas release from the liquid and eventually also lead to failure of the structure (Deublein and Steinhauser, 2011). Mixing and stirring equipment, and the way it is performed, varies according to reactor type and TS content in the digester. In the three most prevalent AD technologies typical for developing countries (fixed-dome, floating dome, tube digester, see chapter 3.4) no stirring is typically implemented. Removing digestate outflow (equivalent to the normal daily feeding load) and feeding this back into the digester through the inlet achieves a passive mixing process. Such a recirculation of digestate also helps to flush the inlet pipe and improves mixing of fresh feedstock with bacteria-rich digestate.

Inhibition

When planning and operating a biogas plant, aspects which inhibit the anaerobic process need to be considered. Some compounds at high concentrations can be toxic to the anaerobic process. Generally speaking, inhibition depends on the concentration of the inhibitors, the composition of the substrate and the adaptation of the bacteria to the inhibitor. Deublein and Steinhauser (2011) list the following typical inhibitors: Oxygen, hydrogen sulphide (H_2S), organic acids, free ammonia, heavy metals, tannins/saponins/mimosine and others hazardous substances such as disinfectants (from hospitals or industry), herbicides, insecticides (from agriculture, market, gardens, households) and antibiotics.

Ammonia nitrogen is often referred to as one of the common inhibiting substances of AD. Ammonia inhibition can take place at a broad range of concentrations. Different studies report ammonia inhibition between 1400 and 17 000 mg N/L of total inorganic nitrogen (Chen, Cheng & Creamer 2008). In anaerobic reactors the total inorganic nitrogen consists mainly of ammonia (NH_3) and the protonised form of ammonium (NH_4^+). At normal pH ranges the biggest share of the total inorganic nitrogen is in the form of ammonium. With increasing pH value and temperature the share of ammonia increases. The undissociated ammonia form diffuses through the cell membranes and inhibits cell functioning by disrupting the proton and potassium balance inside the cell (Kayhanian, 1999). This inhibition will cause an imbalance and accumulation of intermediate digestion products such as volatile fatty acids (VFA) which can result in acidification of the digester. Generally, it is agreed that with long enough adaptation periods, anaerobic microorganisms can tolerate higher ammonium concentrations than those typically measured. However, this may result in a reduction in methane production.

3.3 Classification of AD technologies

Numerous AD technologies for the treatment of biowaste have been developed worldwide and the decision maker is confronted with an extensive number of technical options from which to choose. Digesters range in complexity from simple cylindrical cans with no moving parts to fully automated industrial facilities. Biogas systems can be classified according to critical operating parameters and elements of reactor design. This book does not cover all design options but rather focusses on those that are considered appropriate for the developing country context and for a biowaste feedstock. The following sections discuss the main distinguishing features of selected AD systems.

Total solids content (wet/dry systems)
Depending on the TS content of the substrate fed into an AD system, digester designs are defined as either wet or dry systems. According to Ward et al. (2008), wet bioreactors have a TS content of 16 % or less, while semi-dry and dry bioreactors range between a TS content of 22 and 40 %. According to Li et al. (2011), dry systems are considered better than wet AD for a number of reasons. Dry digestion requires a smaller reactor volume, lower energy requirements (if heating is required), and minimal material handling efforts. Due to the low moisture content of the digestate after dry AD it can easily be used as fertiliser or be pelletized and serve as biomass fuel. Despite these numerous advantages of dry AD and the continuous progress in system design, a number of practical barriers still hinder commercialization of this technology in a developing country context. One barrier is the typical batch wise process (described in more detail below) and another is the filling and emptying process which requires a large enough opening which regularly needs to be sealed in a gastight manner.

Feeding mode (continuous/batch)
Anaerobic digesters can be fed continuously or batch-wise. In a continuous feeding mode, new feedstock is added at regular intervals while an equivalent volume of slurry leaves the digester, thereby providing a continuous process of digestion. Traditionally, most biogas plants in developing countries are operated in continuous mode.

In batch-fed digesters, the reactors are filled with a feedstock, closed and left for a period of time (i.e. the retention time), then opened again and emptied (Khalid et al., 2011). Vandevivere et al. (2003) state that batch systems represent the lowest-technology of all systems and are also the cheapest. Due to their simple design and lower investments costs, batch systems are recommended for application in developing countries. However, experience shows that these reactors have some serious limitations. Each batch, once closed, undergoes the whole start-up phase of the methanogenic process. This implies that there will be high fluctuations in gas production until the system operates in a stable way. Variations are also observed in gas quality. The height of the reactor is limited to ensure good infiltration of the percolate. Furthermore gastight sealing of inlet/outlet can be challenging especially as the doors are regularly closed and opened after each batch sequence. This may result in biogas losses and the risk of explosion when emptying as residual methane in the reactor mixes with air (Vandevivere et al., 2003).

Operating temperature (mesophilic/thermophilic)
As described previously, temperature is an important operational parameter and can also be used to classify AD systems into two categories: mesophilic (30 – 40 °C) and thermophilic (45 – 60 °C) systems. The range below 20 °C is termed psychrophilic and is not suitable for anaerobic digestion as the reaction rate is very slow. Mesophilic systems are considered more stable and require less energy input than thermophilic digestion systems. However, the higher temperature of the thermophilic digestion systems facilitates faster reaction rates and faster gas production. Operation at higher temperatures also facilitates hygienisation of the digestate. As in developing countries with a tropical climate, the prevailing systems are not heated and are therefore typically operated in the mesophilic temperature range.

Number of stages
The rationale of two- and multi-stage systems is to sequence the biochemical reactions that do not necessarily share the same optimal environmental conditions. Rapport et al. (2008) state that single-stage systems are simple, easy to design, build and operate and are generally less expensive than multi-stage systems. They are therefore generally the more appropriate and predominant system applied to full-scale biowaste AD treatment. According to Nichols (2004), single-stage is used mainly for small, decentralized waste management units, while multi-stage digestion is suitable for plants with a capacity of more than 50 000 tons/year.

3.4 Anaerobic digestion technologies for biowaste in developing countries

The choice of the basic AD design is influenced by the technical suitability, cost-effectiveness, and the availability of local skills and materials. In developing countries, the design selection is largely determined by the prevailing and proven design in the region, which in turn depends on the climatic, economic and substrate specific conditions (Lohri, 2012).

The three main types of digesters that have been implemented in developing countries are the fixed-dome digester, the floating-drum digester and the tubular digester, all of which are wet digestion systems operated in continuous mode under mesophilic conditions. These three types are inexpensive, built with locally available material, easy to handle, do not have many moving parts and are thus less prone to failure. A further digester type, the garage-type digester, which is operated as a dry digestion system in batch-mode, is considered as another potential biogas technology suitable for developing countries. Although this technology is being tested in Ghana by converting a used shipping container, it is not yet ready for the commercial market as no viable low-cost design exists that has been successfully tested at full-scale.

Figure 5 provides a systematic classification whereby four digester types are selected as potentially feasible for developing countries and each is described in more detail in the following sections. A good overview of systems is also provided in Fact Foundation (2012).

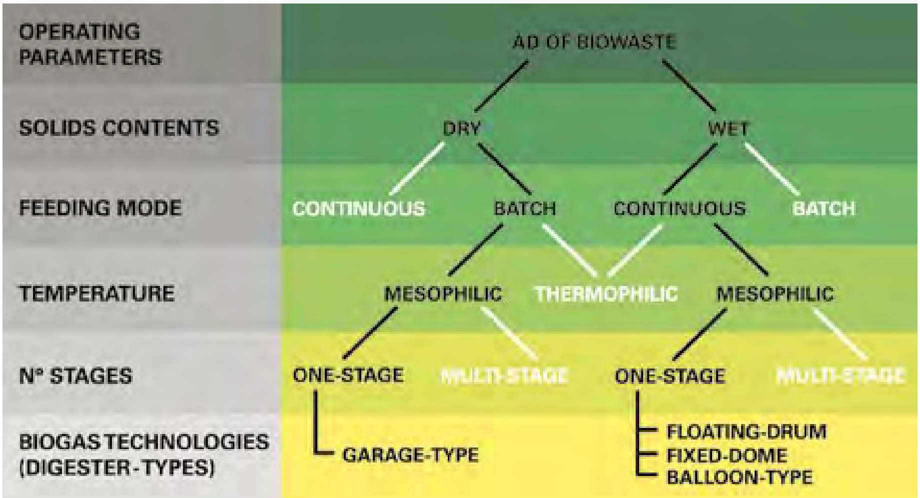


Figure 5: Biogas digester types considered for developing countries that are presented in this book.

3.4.1 Fixed-dome digester

A fixed-dome plant is comprised of a closed dome shape digester with an immovable, rigid gas-holder, a feedstock inlet, and a displacement pit, also named the compensation tank. A schematic diagram is shown in Figure 6. The gas produced in the digester is stored in the upper part of the reactor. With a closed outlet gas valve, increasing gas production elevates the gas pressure inside the digester thereby pushing the digestate into the compensation tank. When the gas valve is open for gas utilisation, gas pressure drops and a proportional amount of slurry flows back from the compensation tank into the digester. Given this design, gas pressure varies continuously depending on gas production and use. Typically such a plant is constructed underground, protecting the digester from low temperatures at night and during cold seasons. Surrounding soil, up to the top of the gas-filled space, counteracts the internal pressure in the digester (normally 0.1 – 0.15 bar, Werner et al., 1989).

Fixed-dome plants are only recommended for situations where experienced biogas technicians with specific technical skills in construction are available to ensure a gas-tight construction. Generally fixed-dome plants are characterised by modest initial cost and a long operational life (about 15 – 20 years), since no moving or corroding parts are

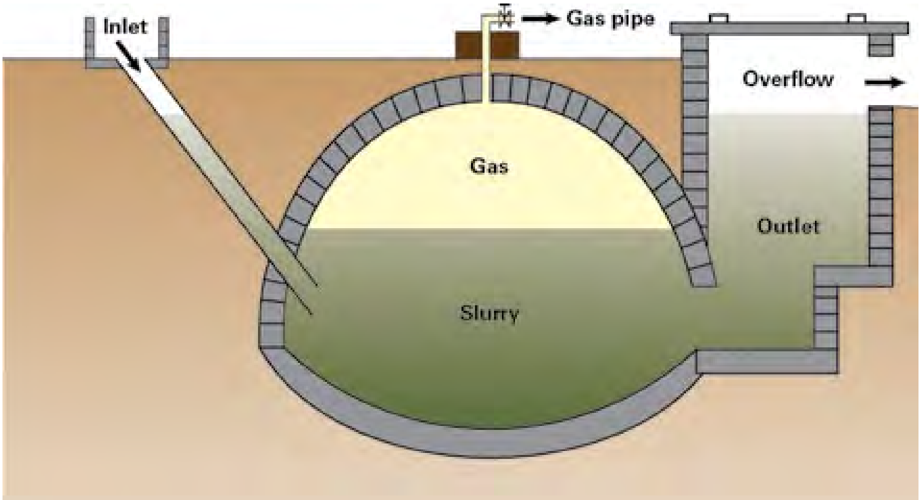


Figure 6: Scheme of fixed-dome digester

required. However with time, the masonry structure may become porous and prone to cracking resulting in gas leakages. Porosity may be counteracted with the use of special sealants, however cracking often causes irreparable leaks. The fluctuating gas pressure in this digester type might complicate gas utilisation (Nzila et al., 2012). A summary of the advantages and disadvantages of this design type is provided in Table 7.

Advantages	**Disadvantages**
• Relative low construction costs • Long life span if well-constructed • Absence of moving parts or corroding metal parts • Underground construction saves space and protects the digester from temperature fluctuations • Local construction provides opportunities for skilled local employment	• Certain specific technical skills are required to ensure a gas-tight construction • Fluctuating gas pressure depending on volume of stored gas • Special sealant is required for the inside plastering of the gasholder (e.g. bee wax–engine oil mixture, acrylic emulsion) • Gas leaks may occur when not constructed by experienced masons • Difficult to construct in bedrock • Difficult to repair once constructed as the reactor is located under soil

Table 7: Advantages and disadvantages of fixed-dome digesters (Kossmann et al., undated).

There are several designs of the fixed-dome digester such as the Chinese fixed-dome plant, the Indian *Deebandhu*, or the CAMARTEC model developed in Tanzania. Fixed-dome digester can be constructed in different sizes, typically ranging from 6–16 m^3. However the principle design elements of all fixed-dome digesters are the same. Historically the fixed-dome digester type was typically used for cow-dung fed systems, but it is also suitable for processing other waste types such as kitchen waste. In some cases toilets are also connected to the digester to treat human waste, which does not create significant problems. Picture 9 shows a fixed-dome shaped digester in Lesotho during construction. This system treats wastewater from toilets as well as greywater mixed with kitchen and agricultural waste (see Part 2, case study F).

Picture 9: Fixed-dome digester under construction in Lesotho (photo: Sandec).

3.4.2 Floating-drum digester

A floating-drum biogas plant consists of a cylindrical digester and a movable, floating gasholder (drum). The digester is generally constructed underground (see Picture 10) whereas the floating gasholder is above ground. Smaller household-scale systems may also be fully above ground (see Picture 11). The digester section of the reactor is usually constructed with bricks, concrete or quarry-stone masonry and then plastered. The gas-holder is typically made of metal and is coated with oil paints, synthetic paints or bitumen paints to protect it against corrosion. Regular de-rusting is however essential to ensure sustained use, and the cover coating should be applied annually. A well-maintained metal gas-holder can be expected to last between 3–5 years in humid areas, or 8–12 years in a dry climate. A suitable alternative to standard grades of steel are fibre-glass reinforced plastic (Picture 11) or galvanized sheet metal (Nzila et al., 2012).

The produced gas collects in the gas drum, which rises or falls again, depending on the amount of gas produced and used. The drum level thus provides a useful visual indicator of the quantity of gas available. The gas is provided at a relatively constant pressure, which depends on the weight of the drum. To increase gas pressure, additional weights can be added on top of the gasholder. Braces can be welded onto the inside of the drum which then help to break up the scum layer when the drum is rotated.

The gasholder floats either directly on the fermenting slurry or in a specifically constructed separate water jacket which reduces methane leakage as shown in Figure 7. A guiding frame constructed inside of the gas drum is an additional measure to avoid tilting of the drum when it rises (see guide pole in Figure 7).

The design size of floating-drum plants is flexible, with digester sizes typically ranging between 1–50 m^3. Table 8 highlights the advantages and disadvantages of floating-drum systems.

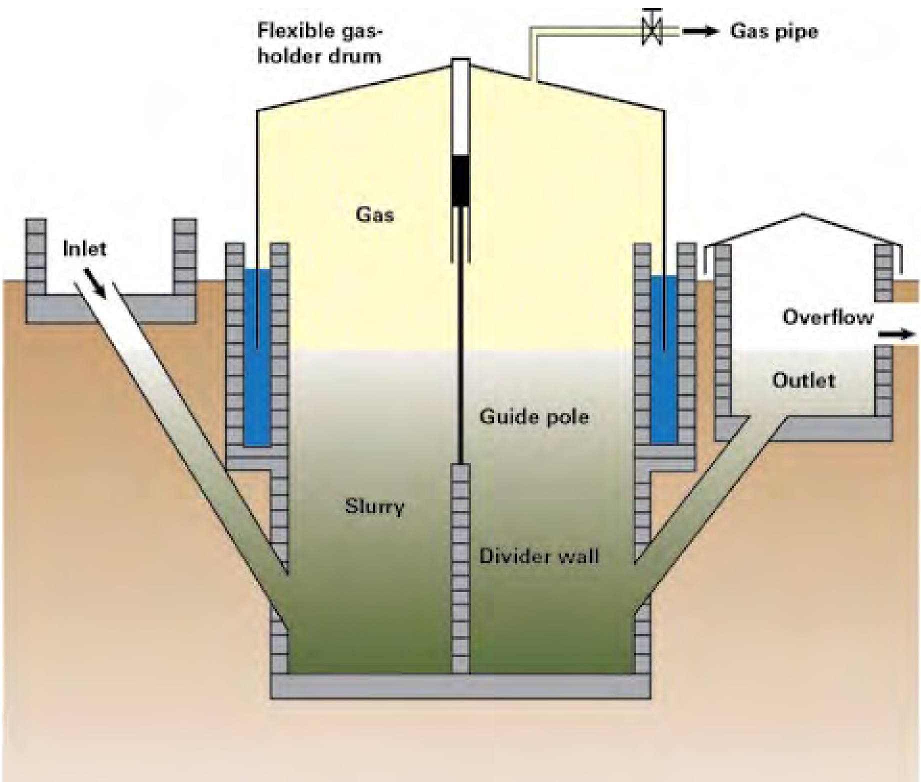


Figure 7: Scheme of floating-drum digester (Estoppey, 2010).

Picture 10: Floating-drum digester for market waste in India (photo: Sandec).

Picture 11: Above ground floating-drum digester for households in India, made of fibreglass reinforced plastic (photo: Sandec).

Advantages	Disadvantages
• Simple and easy operation • The volume of stored gas is directly visible • Constant gas pressure • Relatively easy construction • Construction errors do not lead to major problems in operation and gas yield	• High material costs for steel drum • Susceptibility of steel parts to corrosion (because of this, floating-drum plants have a shorter life span than fixed-dome plants) • Regular maintenance costs for the painting of the drum (if made of steel) • If fibrous substrates are used, the gasholder shows a tendency to get "stuck" in the scum layer (if gasholder floats on slurry)

Table 8: Advantages and disadvantages of floating-drum plants (Kossmann et al., undated).

3.4.3 Tubular digester

A tubular biogas plant consists of a longitudinal shaped heat-sealed, weather resistant plastic or rubber bag (balloon) that serves as digester and gas holder in one. The gas is stored in the upper part of the balloon. The inlet and outlet are attached directly to the skin of the balloon. As a result of the longitudinal shape, no short-circuiting occurs, but since tubular digesters typically have no stirring device, active mixing is limited and digestate flows through the reactor in a plug-flow manner. Gas pressure can be increased by placing weights on the balloon while taking care not to damage it. Figure 8 shows a schematic representation of a typical tubular digester.

The benefit of these digesters is that they can be constructed at low cost by standardised prefabrication. Additionally, the shallow below ground installation makes them suitable for use in areas with a high groundwater table. However, the plastic balloon is quite fragile and susceptible to mechanical damage and has a relatively short life span of 2–5 years (Nzila et al., 2012).

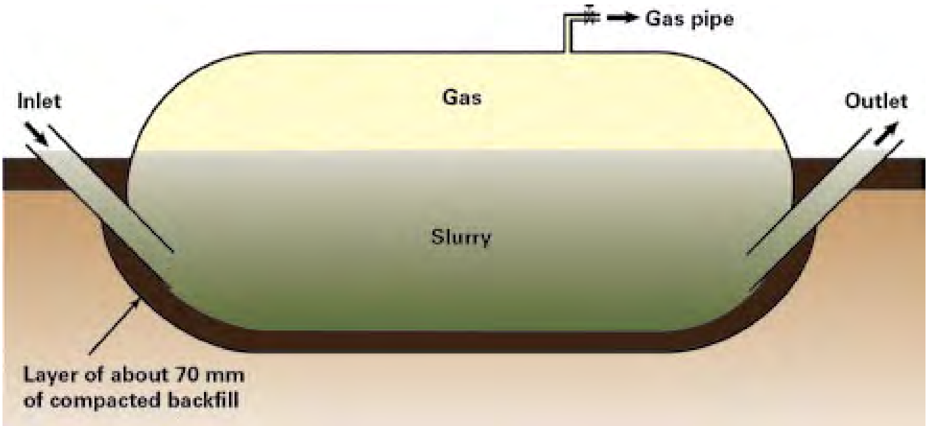


Figure 8: Scheme of balloon digester.

To avoid damage to and deterioration of the balloon, it is also important to protect the bag from direct solar radiation with a roof. Additionally wire-mesh fence protects against damage by animals. Table 9 highlights the advantages and disadvantages of this design type.

Advantages	Disadvantages
• Low construction cost • Ease of transportation • Easy to construct • High digester temperatures in warm climates • Uncomplicated emptying and maintenance • Shallow installation depth suitable for use in areas with a high groundwater table or hard bedrock	• Relative short lifespan • Susceptibility to mechanical damage • Material usually not available locally • Low gas pressure requires extra weights • Scum cannot be removed from digester • Local craftsmen are rarely in a position to repair a damaged balloon

Table 9: Advantages and disadvantages of balloon digesters (Kossmann et al., undated).

The tubular system can be modified in order for it to work at different altitudes and climates. For example, on the Bolivian Altiplano (more than 4 000 m about sea level), biodigesters are enclosed in a polyethylene greenhouse, supported by two lateral adobe walls along the whole length of the shallow trench. A layer of insulating material of at least 20 cm (e.g. natural grass and dry cereal straw) can be used to reduce heat loss through the walls of the trench (see Picture 12). The lateral walls accumulate the heat so that with freezing temperatures during winter nights, the digester remains operational by its high thermal inertia. Furthermore, dark pipes are installed to pre-heat the water used for mixing the substrate before entering the balloon (Herrero, 2008).

Picture 12: Tubular digester in Yanaoca, Cuzco (photo: Herrero, 2007).

Picture 13: Tubular digester in Costa Rica (photo: Sandec).

3.4.4 Garage-type digester

In contrast to the three digester types described previously, the garage-type digester is operated in batch-mode and in a dry digestion process. The entire organic waste stream is filled batch-wise into a simple garage-like digester with an airtight door (Figure 9). Once the door is closed, the material does not need to be transported or turned during the process.

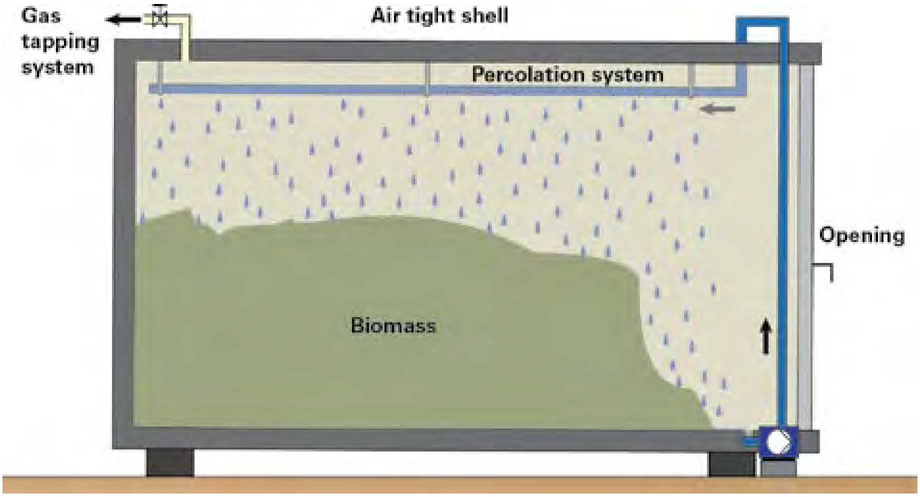


Figure 9: Scheme of a garage-type dry digestion plant.

The term "dry digestion" can be misleading as in every biological process, water plays a crucial role. All bacteria involved in the AD process require a wet environment as they are only active in the liquid phase of the substrate. The term dry digestion therefore refers to a high total solids content above 15 % (Li, Park & Zhu, 2011) compared to wet systems. However the main criterion is the feedstock stackability.

As a general rule, the fresh feedstock material is inoculated with old digestate material or with fresh cow dung in order to initiate and accelerate decomposition by anaerobic bacteria. After closing the digester doors, the percolation system – a shower like installation at the roof of the digester, is put into operation (Picture 14). It sprinkles percolate over the biomass and disperses the AD bacteria evenly in the system. This percolate trickles down through the feedstock material, drains at the bottom of the reactor and is collected in an external storage tank. The percolate is then recirculated with a pump to sprinkle the biomass regularly. An appropriate filter at the percolate outlet prevents coarse particles from entering and blocking the pump and recirculation pipes.

Percolation can be operated continuously or periodically. A few days before the process is terminated, the percolation is stopped to allow dewatering of the digestate material. Before opening the digester doors, the reactor is flushed with exhaust gas (CO_2) from an engine to avoid the formation of an explosive gas/air mixture (6–12 % biogas in air; Deublein and Steinhauser, 2011) which can result during the opening and emptying process.

In batch-fed systems, several digesters have to run in parallel to ensure a continuous and stable gas production (see Figure 10).

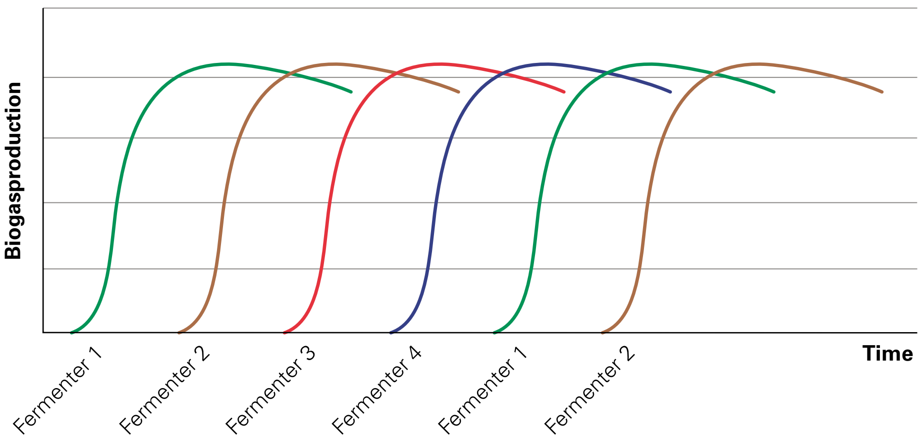


Figure 10: Temporal gas production in parallel operation of different batch digesters (Weiland, 2006).

Dry digestion systems constructed out of gas-tight concrete have been successfully operated in parallel for a number of years in Europe. Experts report that this process has a high potential for successful application in developing countries as it has a very simple design which can be constructed and operated at low cost, only needs little addition of water, and allows easy and safe treatment or use of the residues after digestion. However, to date, there is no available or documented experience of this technology being used in a developing country context. A pilot plant, made from a second-hand shipping container converted into a biogas digester, was tested and adapted at the campus of Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana, starting in 2011 (Picture 15). However, the installation is not yet ready for commercialisation due to persistent problems related to gas-tightness of the digester and related insufficient gas availability (Burri and Martius, 2011; Biolley and Diggelmann, 2011; Robbiani, 2012).

Picture 14: Percolation system made of PVC-pipes (photo: Sandec).

Picture 15: Dry digestion pilot plant at KNUST, Kumasi, Ghana (photo: Sandec).

Table 10 presents the main advantages and disadvantages of garage-type dry digestion plants.

Advantages	Disadvantages
• Simple design • Only little water addition is needed • Easy treatment of digestate	• Gas-tightness of opening difficult • Inoculation is needed for every new batch, thus reducing capacity for fresh feedstock

Table 10: Advantages and disadvantages of dry digester (Burri and Martius, 2011; Biolley and Diggelmann, 2011; Robbiani, 2012).

3.5 Designing the size of an AD system (fixed-dome)

The following section makes use of an example to provide a step-by-step guide as to the process involved in determining required size of an AD system and calculating the expected biogas production.

Background conditions

A boarding school with 250 resident students and 50 staff members (total of 300 people) would like to make use of the organic solid waste they generate each day. Currently this waste is not used and is just been disposed of. The school plans to install a fixed-dome underground digester as the knowledge on how to build and operate this type of AD plant is available locally. The school is in a country with a tropical climate all year round.

Daily per capita biowaste generation

Measurements have shown that each person in the school generates an average of 0.2 kg of organic waste per day (wet weight). This biowaste consists of kitchen and canteen waste (such as vegetable and fruit peelings, and food leftovers). The common canteen is where all students and staff members eat breakfast, lunch and dinner.

Daily total biowaste available as feedstock for AD

The 300 people therefore generate an average of 60 kg/day of biowaste (wet weight). This raw feedstock will be diluted with water in a ratio of 1 part waste to 2 parts water. This will result in a slurry which can be easily flushed into the digester. The daily total quantity of diluted feedstock therefore amounts to 180 L (i.e. 1 * 60 + 2 * 60, using the approximation that 1 kg is equivalent to 1 litre).

Hydraulic Retention Time (HRT)

The ideal HRT for a tropical climate with an average ambient temperature of 25–30 °C is recommended to be around 30 days, which means that an active reactor volume of 5.4 m^3 is required (i.e. 180 L/day * 30 days = 5 400 L).

Feedstock characteristics and Organic Loading Rate (OLR)

The available biowaste (mix of vegetable, fruit and food waste) has a Total Solids (TS) content of 20 %. In other words of the 60 kg wet weight, 20 %, which is equal to 12 kg, is dry matter. The Volatile Solids (VS) content of the dry matter is 80 %, which means that Volatile Solids amount to 9.6 kg and 2.4 kg is non-volatile solids. The balance of the biowaste is water which does not contain Volatile Solids. Therefore of the 180 L of diluted feedstock, the share of Volatile Solids amount to 9.6 kg. Calculated to 1 000 litres (i.e. 1 m^3) of diluted feedstock this is equivalent to 53.3 kg VS/m^3 inflow (9.6 * 1 000/180).

The Organic Loading Rate (OLR) can then be calculated as follows (see Table 6):

$$OLR = Q * S / V$$

Whereby Q is the substrate flow rate (m^3/day), S is the substrate concentration in the inflow (kg VS/m^3) and V is the reactor volume.

Therefore: $OLR = 0.18\ (m^3/day) * 53.3\ (kg\ VS/m^3) / 5.4\ (m^3)$
$= 1.78$ kg VS per m^3 reactor volume and day.

An OLR below 2 kg VS/m^3 reactor volume and day is considered ideal for non-stirred AD systems (see also chapter on OLR under 3.2).

Size of the AD system

A fixed-dome digester (e.g. Nepali GGC2047 model) is designed so that 75 % of the total reactor volume is used for the active slurry and 25 % of the volume is used for gas storage. In this example, this means that the active volume of 5.4 m^3 (equals 75 % of total) is complemented with 1.8 m^3 gas storage volume (25 %), resulting in a total digester volume of 7.2 m^3 for the whole reactor.

Biogas and methane yield

Taking into consideration that a fruit/vegetable/food waste typically yield biogas volumes of 0.67 m^3/kg VS (assuming 0.4 m^3 CH_4/kg VS and methane content of 60 %, see Table 4), it can be expected that approximately 6.4 m^3 of biogas is produced per day (1.78 kg VS/m^3 reactor and day * 0.67 m^3 biogas yield per kg VS * 5.4 m^3 reactor volume, equals to 6.4 m^3/day). This is the biogas flow rate Q_{biogas}. Assuming that the biogas consists of 60 % methane (CH_4), this gives a methane yield of 3.84 m^3/day.

The Gas Production Rate (GPR) can be calculated as follows (see Table 6):

$$GPR = Q_{biogas} / V$$

Therefore: $GPR = 6.4\ m^3/d / 5.4\ m^3$
$= 1.185\ m^3$ biogas/m^3 reactor and day

The Specific Gas Production (SGP) can be calculated as follows (see Table 6):

$$SGP = GRP/OLR$$

Therefore: $SGP = (1.185\ m^3$ biogas/m^3 reactor and day) / (1.78 kg substrate/m^3 reactor and day)
$= 0.67\ m^3$ biogas/kg VS fed material

Biogas utilisation (and value)
An average biogas cooking stove consumes roughly 0.4 m^3 biogas per hour (Kossmann et al., undated; Lohri, 2009a). With the 6.4 m^3 biogas produced in this example a biogas cooking stove can therefore be operated for 16 hours (or 4 hours of cooking on four stoves). As 1 m^3 biogas has an energy content of 6 kWh, the daily produced biogas in this example (6.4m^3/24h) contains 38.4 kWh. Thus the power is 1.6 kW (38.4kWh/24h), of which in a small Combined Heat and Power (CHP) plant (with an electrical efficiency of 30 %) 0.48 kW can be used as electricity whereas 0.88 kW can be used as heat (thermal efficiency of 55 %).

Additional remarks (feeding breaks)
If a summer break of 2–3 months is assumed during which students are not on the campus, no substrate would be added to the digester for this period of time. From a microbiological point of view, this feeding break is not considered a problem. However, it is important that once the feeding starts again, the amount of daily feedstock is gradually increased to avoid shock loads to the bacteria inside the reactor. In practice this means that during the first two weeks after the summer break only 20 % of the normal daily feeding load should be added, increasing this to 50 % over the next 2 weeks, and then finally arriving at 100 % again.

It is important that during the summer break the formation of a thick scum layer is prevented. This is usually not an issue during normal operation as the daily feeding breaks up such scum layers. To avoid scum layer formation during feeding breaks it is therefore advised to remove the equivalent digestate of a normal daily feeding load and feed this amount back into the digester through the inlet. This recirculation of digestate prevents adverse conditions such as the formation of a scum layer or blockage of the inlet pipe by concentrated feedstock still in the inlet pipe from the last feeding.

3.6 Operation and maintenance

Proper operation and maintenance (O&M) of the different technical components of the biogas plant is important to achieve and maintain high levels of gas production and to ensure efficient and long-term performance. A well designed biogas unit should be easy to operate and should only require minimum daily care (Sasse, 1991). It is also important that the labourers and/or plant manager responsible for the operation and maintenance of the plant are provided with proper training and clear instructions so that there is a good understanding of the required tasks and their importance.
It is useful to develop and implement a maintenance strategy that includes clear allocation of responsibilities, a task schedule, and control mechanisms to check if duties have been conducted properly.

An overview of the regular operation and maintenance activities required for a wet continuously-fed AD system is provided in the following sections.

Daily activities

The plant must be fed regularly in order to provide a stable gas production and because the bacteria prefer constant feeding. The feedstock needs to be pre-treated consistently, i.e. particle size of all feedstock must be reduced to 3 – 5 cm in length and mixed with water or effluent from the biogas plant. Impurities (e.g. inorganic materials such as glass, metals, plastics etc.) should be removed before pre-treatment. The amount of daily feedstock should be measured using a scale or using selected containers where the required filling level is indicated (see chapter 2.4 Pre-treatment and feeding procedure).

Weekly to monthly activities

If the biogas is to be used as cooking fuel, the biogas stoves need to be cleaned regularly. Food particles and dust have to be removed to avoid clogging of the air intake holes. Grease should be applied to all movable parts and the air flow intake readjusted. Gas pipes, joints and stove need to be checked to ensure they are still gastight when valves are closed. This can be easily detected either by smell, as biogas contains small amounts of hydrogen sulphide which smells like rotten eggs, or by smearing some liquid detergent onto the place where leakages could be expected. If leaks are present, bubbles will be observed at those locations. Leakages need to be repaired immediately to avoid hazards to the kitchen staff. Condensed water in the pipes should be removed on a weekly to monthly basis to ensure that the biogas can pass through the gas pipe easily. The appearance and odour of the digested slurry needs to be checked on a regular basis. If well digested, the effluent should not have an acidic odour (this would be an indication of overload or imbalanced microorganism population). Checking the pH of the digested slurry by means of litmus paper or a pH-meter can help to examine biological activity. However, it is worth noting that the pH value of the digestate only indicates instability of the anaerobic process when the substrate-specific buffer capacity has already been consumed (Eder & Schulz, 2006). If the pH is below 5.5, feeding has to be stopped and only started again with a gradually increasing feeding rate once the pH has stabilised. The gas pipes above ground, valves, fittings, appliances and gas storage balloons need to be checked for leaks. The section on 'Annual monitoring activities' provides methods on how to examine gas tightness.

Annual monitoring activities (fixed-dome digesters) or tasks to perform when biogas quantity reaching the kitchen is unstable or substantially decreasing

- **Check the gas-tightness of the pipes (pressure-test)**
  Close the main valve (on top of the dome) and connect a gas pressure meter (0 – 160 mbar) in the kitchen ahead of the (closed) kitchen valve. Open the main valve

and wait until the pressure rises up to at least 100 mbar, then close the main valve. Wait 10 minutes. If the pressure decreases by more than 5 mbar, use a soap and water solution to detect the leaks. Necessary repair work can then be undertaken to fix the leaks. Repeat the test until the pressure remains constant.

- **Check the gas tightness of the dome (pressure-test)**
  Connect the pressure gauge right after the main valve on top of the dome. If the pressure, even after several days of no gas being consumed never rises up to the maximum design pressure (i.e. the pressure at which the slurry level in the compensation chamber reaches overflow point), then the dome is probably not gas tight and needs to be checked. Leaks can be detected by applying soap water on the dome, if accessible, and then repaired.

- **Check blockage of inlet pipe**
  Another reason for low gas production is clogging of the inlet pipe. This will eventually prevent feeding substrate into the digester. Depending on the design, the inlet pipes can be unblocked either with a long plastic tube or wooden stick at the feeding point or at the inspection chambers (if available).

- **Check blockage of gas pipe by condensed water**
  Check and empty the condensate water trap.

- **Observe the slurry level in the compensation chamber**
  The level should be high in the morning as gas is produced overnight, and lower during the course of the day when gas is consumed.

- **Check gas-producing activity of digestate**
  If the pH in the digestate is neutral but it is not clear if the slurry inside the digester is still active (i.e. producing gas), the balloon test can be applied. Fill approximately 1 L of slurry in a 1.5 L PET-bottle, put a balloon onto the top of the bottle and seal it with tape to prevent gas escaping. Leave the bottle with the attached balloon for one week in the sun, shaking it carefully on a daily basis to avoid the formation of a hard scum layer in the bottle. If the slurry still contains anaerobic bacteria, the balloon will slowly inflate. However, this method cannot determine the gas content (methane or carbon dioxide).

- **Control the biogas stove**
  The flame at the biogas stove gives some indication on the gas pressure and the combustion (Zifu et al., 2008):
  - Elongated yellowish flame indicates incomplete combustion (i.e. CO, CH_4 emissions in the kitchen), so oxygen intake needs to be regulated.

- Flame lifts off: this indicates excessive pressure (either diameter of injector is too big or valve uncontrolled open, often stoves have a design pressure in the range of 8 to 16 mbar, so higher pressure needs to be avoided).
- Flame extinguishes: indicates little gas flow or low gas pressure. Little gas flow may result from a corroded or blocked injector which must be repaired.
- Flame is small: indicates low gas flow rate which can be a result of a blocked gas pipe (blocked by slurry or water).
- Flame is big: indicates excessive fuel supply. Burner holes may be corroded or too big, or else the injector diameter is too big.
- Thick reddish or fluttering flame or flame too small: indicates low flow rate (blocked gas piping by slurry or water).

- **Protect metal drum of floating drum digester**
  For metal floating drum digesters the gasholder drum needs to be removed and the inside repainted with anticorrosive paint on an annual basis.

- **Remove the accumulated sludge on the bottom of the digester**
  If all the above measures have been performed but the gas production is still very low, it may be that over the years the active reactor volume has decreased because of accumulated sludge on the bottom of the digester. In this case, the sludge needs to be manually removed from the bottom of the digester. The frequency of desludging depends on many parameters but typically, if properly designed and operated, sludge emptying should only be necessary every 5–10 years. When removing the digester slurry and sludge through the compensation chamber, it is important to ensure that the health and safety of the labourers is not compromised. Prior to entering the digester, open all the gas valves and flush out the gas holder with exhaust gas from an engine. Ensure good ventilation before entering the digester and be aware of the risk of explosion.

Regular monitoring of the biogas production is useful as the operator then learns to detect disturbances in the biology inside the digester. However, as no simple, reliable and inexpensive biogas flow meters are available and experience shows that this extra-effort by operators cannot be expected and ensured, regular measurement of the daily gas production is not considered essential. This implies that the operator must react quickly when observing problems. Table 11 lists some common problems observed in low-tech AD systems and describes the possible reasons and solutions to these problems.

Observation of Problem	Possible Cause	Solution
Gas production is low	• Insufficient feeding of substrate	• Add more substrate as related to size of reactor
Gas pressure is low or continuously decreasing even if gas is not used	• Blockage of gas pipe by slurry • Gas pipe or valve is leaking • Leakage due to a crack in the dome (worst-case scenario)	• Disconnect gas pipe from digester. Compress air through pipe to unclog what may cause blockage • Conduct pressure test and use soap water (liquid detergent) to check for leakages of valves and joints. Also check that water trap and/or valve of outlet pipe is tightly closed • The reactor must be emptied and the cracks repaired
Gas pressure is as usual but gas supply runs out quickly	• Scum on surface of digester chamber	• Use stick to stir (through inlet or outlet) until scum is dissolved • Remove digestate from the outlet and recirculate through the inlet pipe to achieve a mixing effect
Gas pressure is not consistent	• Condensed water has accumulated in gas pipe	• Open water trap valve to empty condensed water in the pipe • Make sure the water trap is at the lowest point of the whole gas piping system
Gas has a bad smell and is non-flammable	• If pH is acidic (< pH 6), this indicates too much acid in the system and an imbalance of microbial communities • Hazardous antiseptic or other toxic material which were mixed in the feedstock have inactivated some of the bacteria	• Stop adding substrate for 2–3 days and check if the gas becomes flammable • Add digestate mixed with lime through the inlet pipe to increase pH and control pH with an acid-base indicator strip
Gas is odourless and non-flammable	• Too much air supply in the burner	• Adjust air adjustment ring at nozzle of burner
Uneven flame	• Water is trapped in gas pipe	• Open water trap valve to empty the water and then close valve tightly
Low flame	• Low gas pressure due to leakage • Low gas pressure if most of the stored gas has been consumed (in fixed-dome systems) • Nozzle hole of burner is too small or flame ports of burner are blocked	• Check biogas plant and gas pipes and valves for leakage • Stop using gas for a day and see if the gas pressure builds up again • Enlarge nozzle hole diameter or clean flame ports of burner
High flame	• Nozzle hole is too big	• Reduce nozzle hole diameter
Yellow flame instead pale blue flame	• Nozzle hole is to wide	• Regulate air injection until flame is pale blue
Flame returns in gas pipe instead of going up through burning holes	• Flame ports are blocked	• Clean/unclog flame ports with a nail or clean it by using a wire brush to scrub and remove sediment and dirt from burner cap

Table 11: Trouble-shooting in AD systems (adapted from Werner et al., 1989).

4. Utilisation of Biogas

4.1 Biogas storage

Biogas generation varies during the day according to feeding patterns and ambient temperature changes. In addition, gas production continues during the night. This means that biogas generation and consumption often do not happen at the same time. It is thus necessary to collect the produced biogas temporarily in appropriate storage facilities. Biogas can be stored in a gastight container for long periods of time without losing its energy content. This is a clear advantage over other renewable energies such as solar or wind energy. A disadvantage of biogas is the relatively small energy density; 1 m^3 (1 000 litres) of biogas contains only as much energy as 0.6 to 0.7 litres of fuel oil (6 kWh). If not compressed, biogas needs a big storage volume (Eder and Schulz, 2007).

All biogas storage facilities whether made of rigid or flexible material, must be gas tight and pressure-resistant. Additionally, any type of storage facilities that are not inside a building must be UV-, temperature- and weather-proof.

The size of the gas storage container is determined by the rate of gas production and rate of biogas usage. The easiest way to store biogas is in low-pressure systems such as a floating-drum, a fixed-dome or in a gas storage bag (balloon), all of which are used in developing countries.

4.1.1 Low-pressure storage systems

This section describes the various low pressure storage systems in more detail.

Floating-drum

In a floating-drum biogas plant (see chapter 3.4.2), the drum serves as the gas storage facility. The produced gas fills the drum and pushes it upwards. The more gas that is produced, the higher the drum rises as illustrated in Picture 16 (see also Figure 11).

When gas is extracted from the drum through a valve for subsequent use, the volume contained in the floating-drum decreases and the drum sinks back down. The weight of the drum itself exerts pressure on the gas within. This ensures a specific gas pressure which is more or less constant irrespective of how much gas is in the drum. This

Picture 16: Rising floating-drum with increased gas production. ARTI system, Tanzania (photo: Sandec).

gas pressure is sufficient to operate a normal gas stove. If a higher gas pressure is required, placing stones, a concrete block, or old tires on top of the drum adds additional weight to the drum (see Picture 17). Where the drum floats directly on the slurry inside the reactor, considerable gas losses may occur if the drum does not fit well with the reactor as gas will escape through the gap between the reactor and drum (Voegeli et al., 2009). Such a system can be improved by constructing a water jacket. The drum then does not float in the slurry but rather on water in an external rim (Figure 12). In a floating-drum system, a safety valve in the drum is not required as surplus gas will be released from under the rim when the drum becomes overly full and rises beyond a certain point (Ulrich et al., 2009).

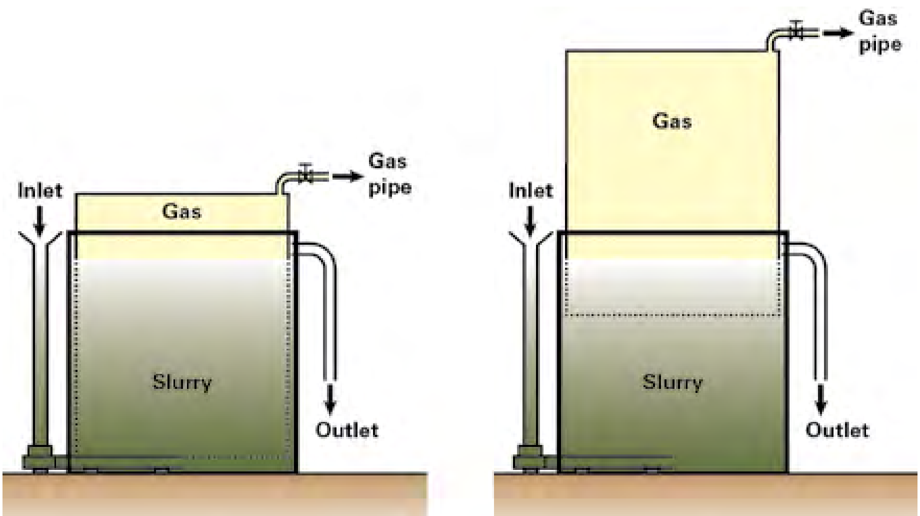


Figure 11: Gas drum empty (left) and filled (right).

Picture 17: Steel floating-drum with water jacket and weight on top of the drum (photo: Sandec).

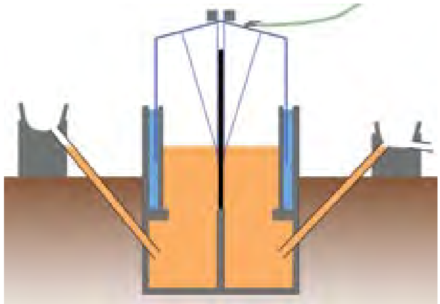


Figure 12: Schematic of a floating-drum with water jacket.

Fixed-dome

The upper part of a fixed-dome digester serves as a gas storage facility (see chapter 3.4.1) and it is therefore essential that it is gas-tight to prevent gas leaks. When the exit valve is closed and gas accumulates in the dome (e.g. during night), the gas pressure will increase and push the slurry in the digester downwards and out into the compensation tank (slurry reservoir, Figure 13). When the valve is opened and gas is consumed, then a proportional amount of slurry flows back into the digester (Figure 13).

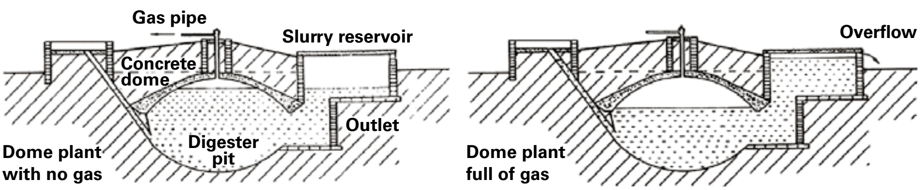


Figure 13: Fixed-dome digester without (left) and with (right) gas pressure [2].

Gas storage bags

Gas storage bags are available in almost any size, but are susceptible to damage by weather or vandalism. The material must be gas-tight, UV-resistant, flexible and strong. PVC is not suitable. The weakest points are the seams and in particular the connections between the foil and the pipes. Balloons should be laid on sand bedding or hung on belts or girdles (Picture 18), and it may be necessary to protect them against rodents. The gas pressure must be kept under control to match the permissible stress of the material, especially at joints. Fitting a safety valve, which functions as a water seal on gas pressure, should solve this problem (Ulrich et al., 2009).

The bags should preferably be produced locally (Picture 18 and Picture 19). If they have to be imported (e.g. from India or Europe), the costs increase substantially.

Picture 18: Gas storage bag in Tanzania (photo: Sandec).

Picture 19: Gas storage bag in India (photo: Sandec).

4.1.2 Medium-pressure storage

Gas storage tank

Where biogas is stored under medium pressure (5 – 20 bar), a gas storage tank is the most suitable system. Due to the resulting higher energy density, it needs less space than the low-pressure options described above. With a compression to 10 bar, 10 times more biogas can be stored than at normal pressure. The compression in this pressure range can be achieved with a single stage compressor. A pressure regulator is then however needed for withdrawal of gas. For gas reservoirs up to 10 bar, energy requirements of up to 0,22 kWh/m^3 should be considered (Al Seadi et al., 2008). Picture 20 shows a gas tank in India with a safety valve on top.

Picture 20: Gas tank in India with 10 bar pressure (photo: Sandec).

4.1.3 High-pressure storage

Gas bottle/cylinder

Storage of biogas under high-pressure (i.e. compression to more than 200 bar) is technically feasible in special gas bottles. It is essential to purify the gas and remove hydrogen and H_2S which lead to corrosion of the gas bottle. Car engines can be operated with high-pressurised biogas (Picture 21 and Picture 22).

This option is only feasible for large-scale biogas plants due to the high costs. About 20 % of the biogas (1–1.5 kWh/m^3 raw gas) is needed to drive the compressor.

Biogas bottling in developing countries is not yet implemented on a large scale. The Indian Institute of Technology (IIT) in Delhi is engaged in research in this field and is operating a demonstration three-wheel vehicle with bottled biogas (Vijay et al., 2006).

Picture 21: Biogas operated vehicle (photo: IIT).

Picture 22: Biogas bottles for vehicle (photo: IIT).

4.2 Biogas flares

Certain situations may arise where more biogas is produced than can be used. Typically this happens when the gas recovery and utilisation system (e.g. the gas cooking stove) is out of operation for some reason, or when unexpectedly large gas production is achieved by certain qualities and quantities of feedstock. In such cases, it is advised to equip the biogas plant with a biogas flare. Flaring the unused excess gas is a safe way to mitigate risks and to avoid uncontrolled release of methane into the environment and thus avoid pollution. Open flares (essentially a burner) with a small windshield to protect the burner are popular given their simple and low-cost design (Al Seadi et al., 2008).

4.3 Conditioning of biogas

When biogas leaves the digester, it is saturated with water vapour and contains high amounts of energy-deficient CO_2 and varying quantities of corrosive and toxic hydrogen sulphide (H_2S). Depending on the use of the biogas, it may have to be cleaned to remove the H_2S or water vapour. This is particularly important when using a gas-driven engine to produce electricity. The main steps of gas cleaning, as practised in developing countries, are described in this section.

4.3.1 Dewatering

Biogas that leaves the fermenter is nearly 100 % saturated with water vapour. Water vapour can lead to corrosion of the energy conversion equipment and therefore has to be removed from the biogas. When biogas moves through the gas pipelines from the digester to the conversion equipment, the vapour cools down on the walls of the sloping pipes and condenses. The accumulation of condensed water may lead to blockage of the gas pipe. When the biogas is pressurised, the water vapour will also condensate.

To avoid these condensation problems, a condensation separator has to be installed at the lowest point of the pipeline. This normally consists of a screw or valve, sometimes connected to a small container where the condensate can drain off. Figure 14 shows an automatic condensate water trap, Figure 15 a manual trap, while Picture 23 and Picture 24 present two low-tech solutions observed in Tanzania.

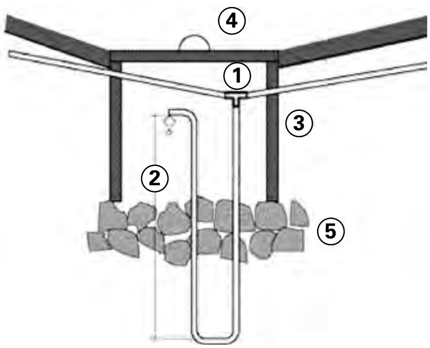


Figure 14: Automatic water trap:
(1) T-joint in the piping system, (2) water column, equal to max. gas pressure + 30 % security, (3) solid brick or concrete casing, (4) concrete lid, (5) drainage [3].

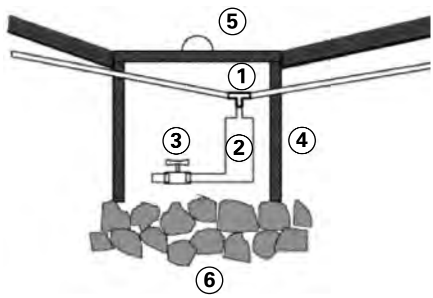
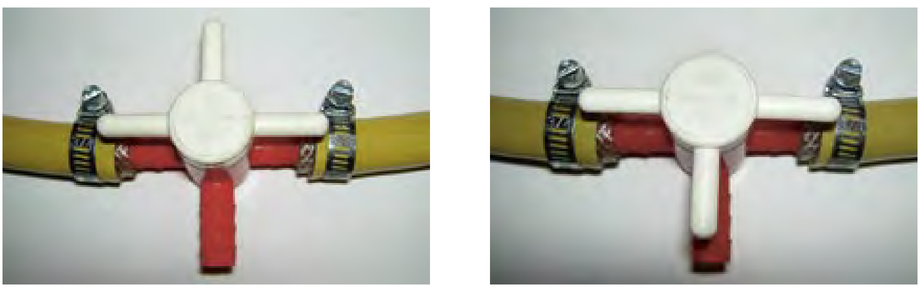


Figure 15: Manual water trap:
(1) T-joint, (2) buffer storage for condensated water, (3) manual tap, (4) casing, (5) concrete lid, (6) drainage [3].


Picture 23: Model "Triple-valve" closed (left) and open (right) (photo: Sandec).

Picture 24: Model made out of garden sprinkler parts in Tanzania (photo: Sandec).

4.3.2 Desulphurisation (removal of H_2S)

Hydrogen sulphide (H_2S), a colourless gas with a distinct smell of rotten eggs, is formed in the biogas plant by the transformation of sulphur-containing protein. H_2S is dangerous as it is toxic in concentrations above 15 parts per million (ppm). However, as it can be smelled at only 0.1 part per million, its presence is usually detected before toxic concentrations are reached. At high concentrations, a person might lose their ability to smell it, which can make H_2S very dangerous (US Dept. of Health and Human Services, 2006). H_2S concentrations in raw biogas are usually between 200 and 2 000 ppm (0.02 – 0.2 %) (Miltner et al., 2012).

For most applications in developing countries, removal of H_2S is not necessary. When biogas is used for cooking and the air-to-biogas proportion is correct during combustion, H_2S is burned and converted directly to sulphur. In incomplete combustion however, sulphur dioxide is produced which can result in headaches and breathing problems. When using biogas to run a combustion engine, it is essential to remove H_2S as it is highly corrosive. Different methods are available for H_2S scrubbing, and two relatively simple methods are described in the following sections. It's important to note that the complete desulphurisation of biogas causes the biogas to lose its characteristic, warning smell. This increases the danger of an unnoticed leak from pipework or equipment.

Removal by ferrous materials (dry desulphurisation)

Hydrogen sulphide reacts readily with iron oxide to form insoluble iron sulphide. The most common method of removing H_2S on small-scale is by using ferrous materials such as rusty iron sponges enclosed in a gas-tight container through which the biogas flows. This is called the dry box method (House, 2010). This method is the only small-scale desulphurising method with acceptable investment and operating costs. The gas to be purified flows through the ferrous absorbing agent from the bottom and leaves the container at the top, free of H_2S. The absorbing material must contain iron in the form of oxides, hydrated oxides or hydroxides. After the reaction is terminated the greater part of the iron is then present as an iron sulphide. By treating the sulphurised absorbent with atmospheric oxygen, iron can be returned to its active oxide form required for the purification of the gas. The used absorbent can therefore be "regenerated". This regeneration cannot be repeated indefinitely, as after a certain time the absorbent becomes coated with elementary sulphur and the pores become clogged. Furthermore, the regeneration process is highly exothermic and must be controlled to avoid problems due to increased temperatures (Muche and Zimmermann, 1985).

Removal by water (wet desulphurisation)

The water scrubber technology is an absorptive method, mostly used for separating CO_2 from the gas stream in medium to large-scale AD plants. The method is based on the physical effect of dissolving gases in liquids. Water scrubbing can also be used to remove H_2S from biogas since both CO_2 and H_2S components have a higher solubility in water than methane. This absorption process is a purely physical process. In high pressure water scrubbing, gas enters the scrubber under high pressure. Then, water is sprayed from the top of the column so that it flows down counter-current to the gas flow. To ensure a high transfer surface for the gas liquid contact, the column can be filled with packing material, preferably plastic structures with a surface to volume ratio of 100–200 m^2/m^3. Mineral surfaces such as lava stones or even gravel can also be used, but these materials tend to clog and they are quite heavy. There have also been attempts to use coconut shells or the like.

Picture 25: Biogas scrubber to remove H_2S at BIOTECH, India. The gas flows upwards through a column in which water containing iron salts is circulating in counter current. The H_2S is dissolved in the water and oxidised (photo: Sandec).

Using this process with a subsequent drying step, achieves a methane purity of up to 98 %. Water scrubbing requires a large amount of water. In regenerative absorption, the washing water is regenerated by depressurising or by stripping with air in a similar column (de Hullu et al., 2008). Picture 25 shows a biogas scrubber from India.

4.3.3 Removal of CO_2

CO_2 is the second most abundant gas in biogas and is present in concentrations between 35–40 %. If CO_2 is removed, the energy available from a unit volume of biogas can be increased considerably. However, since CO_2 does not interfere when using the biogas for cooking, it is therefore normally not removed in developing countries.

Where pressurised storage is used, scrubbing the CO_2 will reduce the capital cost of storage markedly. CO_2 can be removed from the biogas by bubbling the gas through water containing any alkaline chemical (House, 2010).

If biogas is used as a motor fuel, high methane content (> 96 %) has to be reached and removal of CO_2 is essential in order to obtain the quality of natural gas required (Persson et al., 2006).

4.4 Biogas applications

Biogas has many energy utilisations, depending on the nature of the biogas source and the local energy demand. In developing countries it is most commonly used in stoves, lamps and engines.

The energy conversion efficiency of using biogas is 55 % in stoves, 30 % in engines, but only 3 % in lamps. A biogas lamp is only half as efficient as a kerosene lamp. The most efficient way of using biogas is in a heat-power combination where 88 % efficiency can be reached. However, this is only possible for larger installations where the exhaust heat is re-used (Kossmann et al., undated).

Table 12 provides typical utilisation rates of biogas in litres per hour (L/h).

Biogas Application	Consumption Rate (L/h)
Household cooking stove	200–450
Industrial burners	1 000–3 000
Refrigerator (100 L) depending on outside temperature	30–75
Gas lamp, equivalent to 60 W bulb	120–150
Biogas/diesel engine per brake horsepower (746 watts)	420
Generation of 1 kWh of electricity with biogas/diesel mixture	700

Table 12: Consumption rates of different biogas appliances (Kossmann et al., undated).

The following sections describe the most widely used biogas applications in developing countries.

4.4.1 Direct combustion and heat utilisation

Direct burning of biogas in stoves is the easiest way of taking advantage of biogas energy for households in developing countries, thereby replacing traditional cooking fuels like wood, charcoal or Liquefied Petroleum Gas (LPG). Commonly, H_2S or CO_2 is not removed from the gas for this purpose.

General features of biogas stoves

A biogas stove is a relatively simple appliance for direct combustion of biogas. Its burner consists of a premix and multi-holed burning ports and operates at atmospheric pressure. A typical biogas stove consists of a gas supply tube, gas tap/valve, gas injector jet, primary air opening(s) or regulator, throat, gas mixing tube/manifold, burner head, burner ports, pot supports and body frame. A schematic diagram of a typical biogas burner is shown in Figure 16 and a detail view of a self-fabricated biogas stove from Tanzania in Picture 26. A biogas stove can have a single or double burner, varying in capacity to consume from 0.22 to 0.44 m^3 of gas per hour or more (Khandelwal and Gupta, 2009).

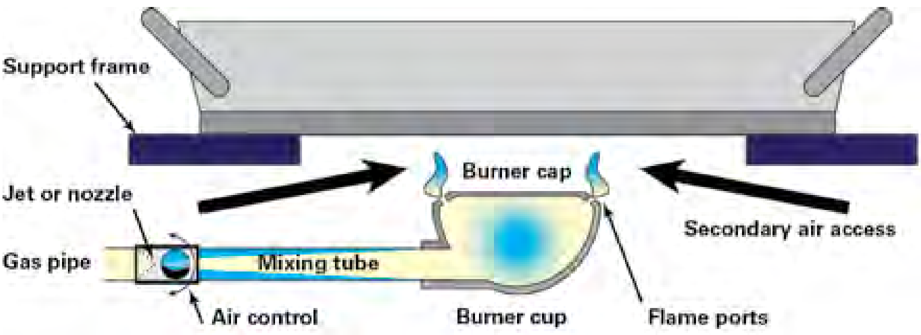


Figure 16: Assembly of a typical biogas burner.

Biogas enters the stove with a certain speed which depends on the gas pressure and diameter of the gas supply pipe. With the help of an injector jet at the inlet of the stove, the gas speed is increased to produce a draft to suck in primary air. The gas and air are mixed in the mixing tube and this gas mixture then enters the burner head. The mixture of gas and air leaves the burner through the ports with a speed only slightly above the specific flame speed of biogas. For the complete combustion of biogas, more oxygen is drawn from the surrounding air, called secondary air.

The main parameters for designing a biogas stove are efficiency and safety, ease of mass manufacturing, and cost-effectiveness. In order to achieve a high efficiency, the following important factors are decisive:

- Gas composition
- Gas pressure
- Flame speed (velocity)
- Pan to burner distance

In general the stove should meet the following criteria:
- Gas inlet pipe should be smooth to minimise the resistance to flow of gas and air.
- Spacing and size of air holes should match with the requirement of gas combustion.
- Volume of burner manifold should be large enough to allow complete mixing of gas with air.
- Size, shape and number of burner port holes should allow easy passage of the gas-air mixture, formation of stabilised flame and complete combustion of gas, without causing lifting of flame off the burner port or a flame back flash from burner port to gas mixing tube and injector jet. The flame should be self-stabilising i.e., flameless zones must re-ignite automatically within 2 to 3 seconds.
- Under ideal conditions, the pot should be cupped by the outer cone of the flame without being touched by the inner cone.

Picture 26: Detail view of biogas stove from Tanzania (photo: Sandec).

A test report and a comparison of different biogas stoves from Bangladesh, Cambodia, Ethiopia, Lesotho, Nepal, Rwanda and Vietnam are available in Khandelwal and Gupta (2009).

Gas demand for cooking

Tests in Tanzania have shown that about 300 litres of biogas are needed to cook for one hour with a simple household stove. This corresponds to the consumption rate for household burners given in Table 12. The tests were conducted without increasing the gas pressure; i.e. no extra weight was placed on top of the gas holder. The pressure in the fermenter was 2 mbar (Lohri, 2009a).

When putting half a cement brick (ca. 12 kg) on top of the gas holder, the pressure in the fermenter increased to 4 mbar and 500 L biogas were consumed in one hour. The increased gas pressure increased the gas flow rate to the cooker and thus reduced the cooking time (Lohri, 2009a). The daily gas demand of a family varies according to their diet and social habits. Research in Nepal revealed that typically 400 L of biogas is consumed per hour with locally constructed household stoves (Lohri et al., 2010).

Table 13 gives some indication on how much gas is used to cook different dishes in India. The gas flow rate of the stove was about 180 L/h.

Item	Gas Required (litres)	Time (min)
1 L water	30	10
3 L water	75	25
500 g rice (3 L water)	205	65
500 g rice (3 L water) with thermal cooker	105	35
10 rice pancakes ("Appam")	70	25
2 steamed rice cakes	45	15

Table 13: Required gas amount and cooking time for various dishes (Estoppey, 2010).

4.4.2 Biogas lamps

In villages without electricity, lighting is a basic need as well as a status symbol. However, biogas lamps are not very energy-efficient and become very hot. If they hang directly below the roof, they may cause a fire hazard (Kossmann et al., undated).

General features of biogas lamps

Biogas can be burnt in lighting mantles. A biogas lamp consists of a gas supply tube, a gas regulator, gas injector jet, primary air hole(s) or air regulator, a clay nozzle, a silk mantle, a lamp shade and a glass shade. A schematic diagram of a biogas lamp is shown in Figure 17 and a biogas lamp from Tanzania is shown in Picture 27.

Picture 27: Biogas lamp from Tanzania before its first use (photo: Sandec).

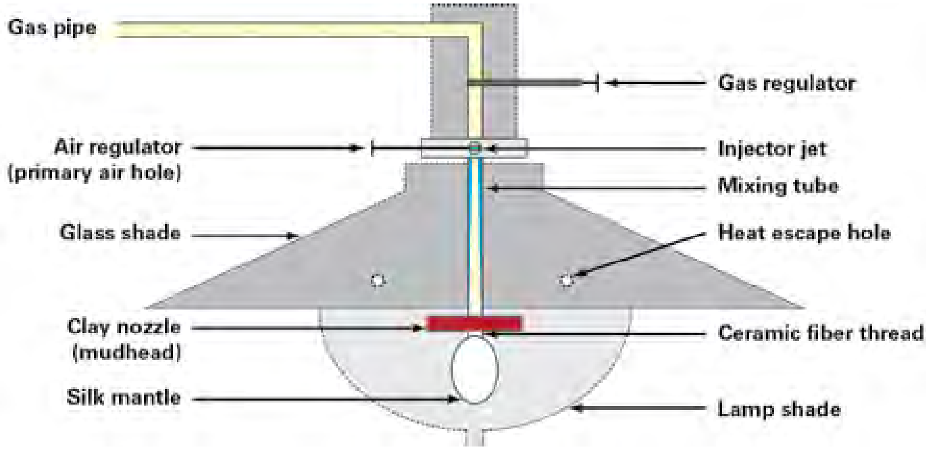


Figure 17: Schematic diagram of a biogas lamp (adapted from Khandelwal and Gupta, 2009).

Mantles, which resemble small net bags, are made by saturating a ramie-based artificial silk or rayon fabric with rare earth oxides such as cerium and thorium (see Picture 27). A binding thread made of ceramic fibre thread is provided for tying it onto the mud head. When heated to a temperature of more than 1 000 °C, the mantle glows brightly in the visible light spectrum while emitting little infrared radiation. Fabric of the mantle, when flamed for the first time, burns away, leaving a residue of metal oxide. Therefore the mantle shrinks and becomes very fragile after its first use (Khandelwal and Gupta, 2009).

The fundamentals of a gas lamp are similar to that of the stove. In a lamp, the burning gas heats a mantle until it glows brightly. The key factors which determine the luminous efficiency are the type and size of mantle, the inlet gas pressure and the fuel-air mixture. The hottest inner core of the flame, should match exactly with the mantle. If the mantle body is too large, it will show dark spots. If the flame is too large, then gas consumption will be too high for the light flux yield. Test results of different biogas lamps from Cambodia, Ethiopia, India and Nepal are described in Khandelwal and Gupta (2009).

4.4.3 Electricity generation

Each cubic meter (m^3) of biogas contains the equivalent of 6 kWh of heating energy. When biogas is converted to electricity in a biogas powered electric generator, about 2 kWh of useable electricity can be obtained and the remaining biogas is converted into heat which can then be used for heating applications. Two kWh is enough to power 20 light bulbs of 100 W each, or a 500 W food blender for four hours. Picture 28 and Picture 29 show a biogas engine from India which is used for public electrical lighting. In order to operate a 2 kW generator continuously, 24 m^3 biogas is needed per day. This would require approximately 240 kg of biowaste per day. Small-scale systems which cannot process these amounts are therefore considered unsuitable as energy suppliers for engines.

Picture 28: Biogas engine (5 kW) in Thiruvananthapuram, India. The electricity is used for public lighting of streets (photo: Sandec).

Picture 29: Chemo-fluorescent lamp run with electricity from biogas (photo: Sandec).

4.4.4 Further applications

Biogas can also be used for other various energy requirements. Refrigerators and heaters are the most common applications. In some cases biogas is also used for roasting coffee, baking bread or sterilising instruments (Kossmann et al., undated).

5. Utilisation of Digestate

In addition to the biogas, the digestate (also called effluent in wet systems) is another valuable product from the anaerobic treatment process. Commonly, the effluent from wet-fermentation biogas plants is a very liquid slurry given its high water content due to the high dilution rate of feedstock and because most of the solids are decomposed during digestion. Storing and handling of this liquid is more complex than solid material such as compost. Picture 30 and Picture 31 show drying beds for AD effluent in Mumbai, India.

Picture 30: Effluent drying bed in Mumbai, India (photo: Sandec).

Picture 31: Effluent drying bed in Mumbai, India (photo: Sandec).

In a rural context, the effluent is a welcome organic fertiliser for agricultural application. In urban areas however, transportation of the effluent to agricultural fields is often not feasible (liquid form, storage, transportation etc.), and application in nearby parks and gardens may be more suitable. Biogas plant operators do not always make use of the effluent and often simply discharge it into the sewer system (Picture 32) or directly into water bodies (Picture 33). The effluent from household digesters treating only kitchen waste is safe for reuse in the garden and is a good organic fertiliser. However, if the feedstock contains human excreta, the effluent quality as it leaves the digester, is not suitable for direct reuse or discharge. In such situations, a post-treatment step of the effluent is needed before safe reuse or discharge can be recommended.

Picture 32: Outlet that is directly connected to sewer system (photo: Sandec).

Picture 33: Biogas plant discharging directly into surface water (photo: Sandec).

5.1 Hygienisation

The anaerobic digestion process cannot ensure inactivation of viruses, bacteria and parasites. The level of hygienisation depends mainly on two parameters: Temperature and Hydraulic Retention Time.

The higher the process temperature, the better the inactivation of microorganisms inside the biogas plant. Only thermophilic digesters reach a sufficient level of microbial disinfection after about two weeks. Although mesophilic digesters result in a significant reduction of pathogens, more time is needed compared to thermophilic conditions. Generally, the longer any organism remains in an unfavourable environment, the more effective is the inactivation (Eder and Schulz, 2007).

Most AD plants in tropical low- and middle-income countries are generally not heated, and are therefore operating in the mesophilic temperature range. Consequently, hygienisation is limited.

Helminth eggs and protozoa accumulate in the sludge at the bottom of the digester. They are therefore largely retained inside the biogas digester, where they remain alive for several weeks. Pathogens, which do not settle but rather remain suspended in the effluent, are hardly affected and exit the plant in their active state (Ulrich et al., 2009).

A study conducted by Lohri et al. (2010) on the performance of institutional biogas digesters treating faeces and kitchen waste in Nepal clearly shows that the effluent still contains a high amount of helminth eggs, although a considerable reduction was achieved inside the digester compared to the influent. Subsequent storage of the effluent in a pond further reduced the number of helminth eggs. Nevertheless the resulting quality only allowed for restricted irrigation according to the WHO guidelines (WHO, 2006).

5.2 Reduction of organic pollutants

Reduction of the organic load is a function of time. The longer the substrate remains inside the digester, the more it is degraded until complete digestion and the maximum biogas yield is reached. In practice however, complete digestion is never the aim as in order to achieve this, the size of the biogas plant required would be disproportional compared to the benefit gained by producing additional biogas.

COD (Chemical Oxygen Demand) is the most common parameter for measuring organic pollution. Effluent regulations for discharge into surface water may tolerate 100 to 200 mg/L COD. High COD discharged into surface waters, will consume oxygen present in that water which is then no longer available to support aquatic life (Ulrich et al., 2009).

Although treating biowaste with AD results in a considerable reduction of COD, the effluent still contains values far above 1000 mg/L COD (Lohri, 2009a; Estoppey, 2010; Gyalpo, 2010). If the effluent is not used as an organic fertiliser but is rather discharged to a receiving water body without further treatment, this would contribute to surface water pollution (see "5.4 Post-treatment of effluent").

5.3 Nutrients / Fertiliser value of effluent

In general, the effluent from AD is a good fertiliser in terms of its chemical composition. All plant nutrients such as nitrogen (N), phosphorous (P), and potassium (K), as well as the trace elements essential to plant growth, are available in the substrate. N, P and K are essential nutrients for plant growth and their relative ratios are of particular importance for soil improvement. However, as each soil type and each plant species has its own specific requirement for N, P and K, a general optimum ratio of these nutrients cannot be determined. In tropical soil, the nitrogen content is not necessarily of prime importance; lateritic soils, for example, are more likely to suffer from a lack of phosphorus instead of nitrogen. Due to these complexities, direct comparison between anaerobic effluent, aerobic compost or chemical fertiliser in terms of their effect on crop quality is not possible (House, 2010).

The C:N ratio decreases during the AD process by transformation of carbon into biogas. A resulting lower C:N ratio (~ 15:1) of the digestate, favours its phyto-physiological effect and thus generally improves the fertilising effect. The phosphate content (P_2O_5 is the form accessible for plants) is not affected by digestion. Some 50 % of the total phosphorous content in digestate is available for plants in the form of phosphate. Similarly, anaerobic digestion does not alter the rate of plant-available potassium (75 to 100 % of the total potassium) (Kossmann et al., undated).

Digested slurry is most effective when it is spread on the fields shortly before the beginning of the vegetation period.

Nitrogen compounds

In contrast to potassium and phosphate, some nitrogen compounds undergo modification during anaerobic digestion. About 75 % of the nitrogen in fresh cow manure is contained in organic macromolecules, and 25 % is available in mineral form as ammonium. There is much less ammonium in organic solid wastes as they have not undergone anaerobic digestion inside the cows (or humans as for excreta, where there is also a substantial part of NH_4-N). In the OFMSW nitrogen is almost completely bound in organic macromolecules. The digestate exiting the reactor contains roughly 50 % organic nitrogen and 50 % ammonium nitrogen but varies, depending on the exact type of feedstock and the retention time in the digester. Ammonium nitrogen can be directly assimilated by plants, while organic nitrogen compounds must first be mineralised by microorganisms in the soil.

Nitrogen and phosphorous are essential plant nutrients and discharge of these compounds into water bodies can enhance algal growth, which in turn, leads to excessive oxygen consumption within the water body. This can reach a level where other aquatic life-forms can no longer survive. Thus effluent should therefore not be discharged into open water bodies without first eliminating the nutrients (Kossmann et al., undated). Care must also be taken to avoid application of excessive amounts of slurry onto soils in certain seasons as this can lead to increased runoff from soils into ground and surface water and their subsequent eutrophication.

5.4 Post-treatment of effluent

As described above, the effluent should never be discharged directly into water bodies without prior treatment. Also spray irrigation onto vegetables should be avoided without prior treatment as there is a risk of pathogens being present in the effluent (Mang and Li, 2010). Unfortunately, experiences from developing countries show that a post-treatment step is seldom implemented.

Appropriate solutions to treat the effluent and sludge of AD plants connected to toilets have been developed in line with the DEWATS approach. DEWATS stands for "Decentralised Wastewater Treatment Systems" and practical guidelines have been developed by WEDC[1] in association with BORDA[2] (Ulrich et al., 2009).

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1 Water, Engineering and Development Centre (WEDC), Loughborough University, UK
2 Bremen Overseas Research and Development Association (BORDA), Germany

DEWATS applications are designed to be low maintenance and the system operates with minimal electrical energy input. They are designed to be reliable, long lasting and tolerant towards fluctuations in the inflow (Ulrich et al., 2009).

Elements of a DEWATS for treatment of AD effluent include the following:
- Sedimentation of sludge and primary treatment in sedimentation ponds, septic tanks, or Imhoff tanks.
- Sedimentation of sludge and anaerobic treatment in baffled reactors (baffled septic tanks) or fixed-bed anaerobic filters (Picture 34).
- Aerobic/anaerobic treatment of non-solids effluent in constructed wetlands (subsurface flow filters) (Picture 35).
- Aerobic/anaerobic treatment of non-solids effluent in ponds.

Picture 34: Anaerobic baffled reactor under construction. TED-BORDA Lesotho (photo: Sandec).

Picture 35: Newly constructed planted gravel filter with ABR (on the right). TED-BORDA, Lesotho (photo: Sandec).

More details on these treatment systems can be found in the following publications:
- *Decentralised Wastewater Treatment Systems (DEWATS) and Sanitation in Developing Countries* (Ulrich et al., 2009).
- *Compendium of Sanitation Systems and Technologies* (Tilley et al., 2008).
- *Greywater Management in Low- and Middle-Income Countries* (Morel & Diener, 2006).

Where the digestate is in solid form (e.g. after dry digestion or after drying of effluent), composting is a suitable post-treatment option. High temperatures during the composting process results in a hygienised product. The diagram in Figure 18 shows the relationship between temperature and time required for pathogen inactivation. If the digestate contains faecal matter, it has been shown that treatment for one week at 50° is sufficient to inactivate all pathogens (red line in Figure 18).

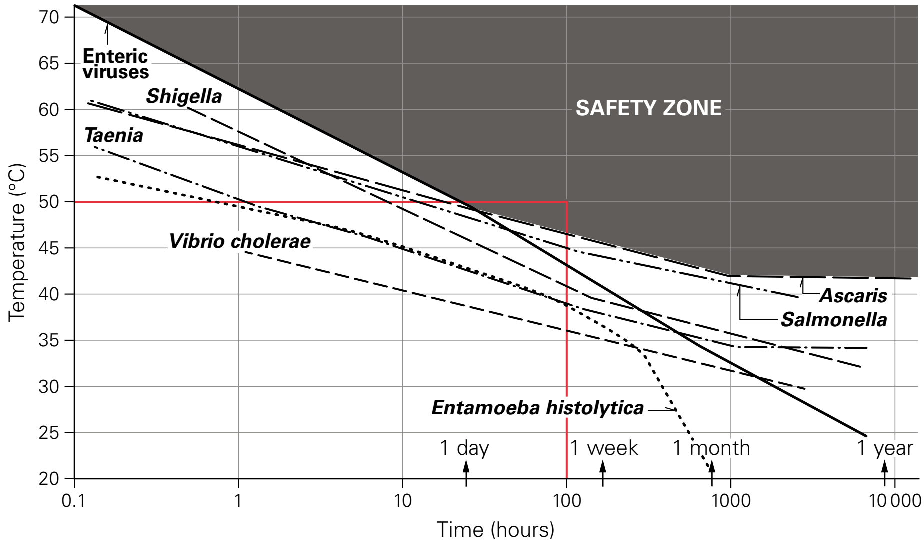

Figure 18: Relationship between temperature and time required to inactivate pathogens (Faechem et al., 1983).

5.5 Instructions for irrigation

Even after post-treatment of effluent and digestate in a DEWATS system, the materials from biogas plants which contain human faeces or animal manure, should be handled carefully as they cannot be considered completely safe. Irrigating non-food crops (trees, flower gardens, etc.) and green spaces is ideal. However, if the aim is to reuse effluent for irrigation in agriculture, the recommendations in the WHO guidelines "Excreta and greywater use in agriculture" should be consulted (WHO, 2006). These guidelines recommend that, if used for unrestricted irrigation, treated wastewater should contain less than 10 000 faecal coliforms per litre and less than 1 helminth egg per litre. As this quality can typically not be achieved in effluent from anaerobic digesters connected to toilets, the following precautions must be taken:

- Effluent should not be spread onto plants which are eaten raw (e.g. lettuce) for at least two weeks prior to harvesting.
- Root crops like potatoes or carrots (except for seeds or seedlings) should not be irrigated with effluent since bacteria and viruses stay alive much longer in soil.
- Workers should take protective measures, such as the use of boots and gloves.

6. Sustainability Aspects

An AD system needs to be compatible with the existing local context in order to guarantee sustainable long-term operation. It is thus essential to consider all influencing factors and ways in which an AD installation can be sustained locally.

An in-depth feasibility assessment is recommended before implementation of an AD-project. Figure 19 illustrates a framework for a feasibility assessment along four different, yet interrelated dimensions that influence the outcome of an urban AD project. Each dimension is equally important and answers a specific question:

1. **WHY?** What are the driving forces and motivations behind the initiation of the AD project?
2. **WHO?** Who are the stakeholders and what are their roles, powers, interests and means of intervention?
3. **WHAT?** What are the proposed physical components and flows in the AD chain?
4. **HOW?** How is the enabling environment (technical-operational, environmental, financial-economic, socio-cultural, institutional, policy & legal aspects) in the proposed AD system?

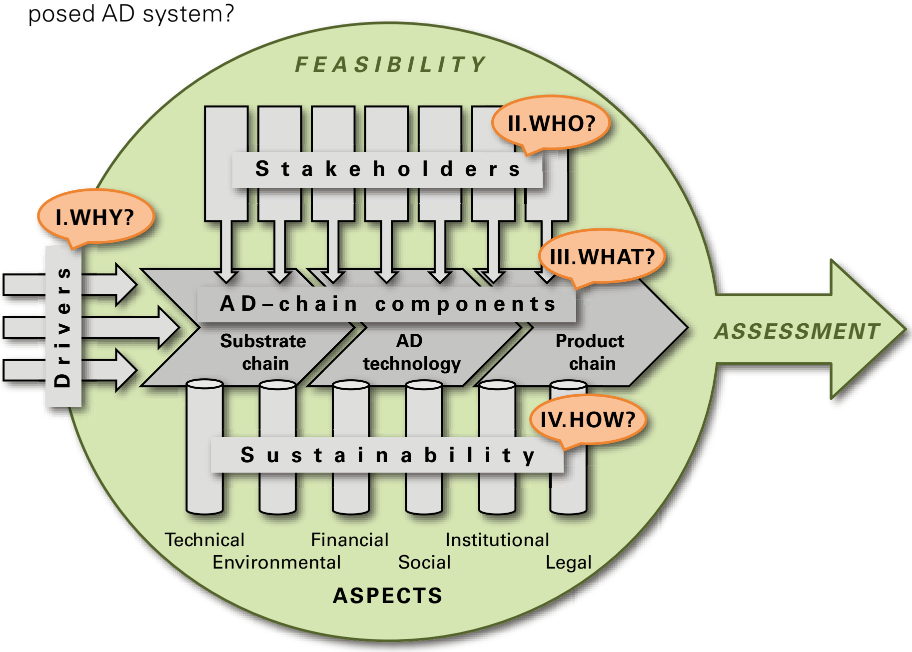

Figure 19: Scheme of the feasibility assessment tool for urban anaerobic digestion in developing countries (Lohri, 2012).

The complete feasibility assessment tool with the detailed set of questions related to these four dimensions is available for download from http://www.eawag.ch/forschung/sandec/publikationen/swm/index_EN

The following sections briefly present the main points to be considered with regards to economic, environmental and socio-cultural aspects.

6.1 Economic aspects

The costs of an AD plant varies widely depending on the country, the technology used, and other factors such as the funding sources, supply chain, and market demand situation. Although no cost figures are provided here, this section presents the main economic aspects that need to be considered. Some cost figures can be found in the case studies in Part II of this publication.

Funding situation
It is important to assess the funding situation and sources for an AD project, as the funding conditions can be either supportive, neutral or disruptive. When taking out a loan, the factors to consider are payback period and interest rate. Questions that need answering are whether financial incentives are provided by local or regional authorities and what role carbon trading mechanisms (Clean Development Mechanism) might play in the financial scheme.

Clean Development Mechanism
Clean Development Mechanism (CDM) is a market-based mechanism that was defined in the Kyoto Protocol to allow trans-boundary cooperation in carbon emission reductions. With the support of the CDM, developing countries can sell Certified Emission Reductions (CERs). Each CER earned is equivalent to one ton of CO_2 equivalent avoided as compared to a certain baseline. These CERs can be bought by industrialised countries to meet a part of their emission reduction targets (UNFCCC, 2010). Before validation for CDM, all projects must qualify through a rigorous and public registration and issuance process designed to ensure real, measurable and verifiable emission reductions. The CERs or the emission reduction are calculated by comparing the actual level of emissions by implementation of the project with the baseline emissions that would have been emitted in the absence of project (UNFCCC, 2010). High transaction costs until registration and a volatile market price for CERs are considered a major obstacle for using CDM as a financial contribution for small-scale AD projects.

Market demand situation

An AD system can only be operated sustainably if there is a demand for its products (biogas and digestate). On both a household and institutional scale (e.g. restaurants, hotels, schools, hospitals etc.) an AD plant operated with biowaste is seldom seen as a way to reduce and treat the amount of waste requiring disposal. Rather, it is perceived as a simple way to replace some of the costs of cooking fuel by making use of the biogas and perhaps also to substitute artificial fertiliser by the digestate. In this case, demand for the products of AD is met by the operators of the facility. On a municipal scale however, a comprehensive market demand analysis is needed. This essentially provides an answer to the question: Is there a promising market for the AD products? Aspects to be addressed include:

- What is the profile of the targeted customer for biogas and/or digestate?
- How large is the demand for the products, and what is the customers' willingness and ability to pay?
- Which other factors (e.g. competitors) influence the sales of products from AD?
- How can the 4 P's of marketing (product, price, place, promotion) for the AD products be described?

The book "Marketing Compost" describes a detailed marketing approach for composting. Although developed specifically for compost, this book can be used as a helpful guide to understand the marketing environment, identification of appropriate target groups and development and promotion of products to suit the AD market (Rouse et al. 2008).

6.1.1 Cost-benefit analysis

A cost-benefit analysis helps to evaluate if the annual revenues (or income) are sufficient to pay all the costs incurred; i.e. does the total sum of benefits outweigh the overall costs? Such an analysis needs to list all costs related to an AD installation and all the revenues expected.

Investment costs (also called capital expenditures CAPEX)

Next to the choice of technology, the investment costs will depend on other factors such as:

- Land space required and costs of land acquisition
- Planning studies and required surveys
- Civil works at the facility including support structures and buildings
- Construction of the digester
- Biogas pipes (connecting systems)
- Large and small mechanical equipment (e.g. shredder)

- Transport of materials (including insurance)
- Customs duties, taxes

Operational costs (also called operational expenditures OPEX)
These costs, also called running costs or recurrent costs, include not only operation of the service but also maintenance of the system as well as depreciation on capital costs (interest rate on loans). At a household level, operational costs are negligible as it is mostly carried out by family members and not by salaried staff. For bigger biogas plants, trained personnel are needed for daily operation. Typical cost factors for larger plants include electricity, water, transport of feedstock, spare parts and staff salaries.

Biogas benefit
The total value of biogas is a function of the net amount available, the value of the fuel it replaces, and the conversion efficiency (House, 2010). Revenue generated therefore depends mainly on what energy source can be replaced by the biogas.

Benefit of effluent as fertiliser
In many studies on the economics of biogas plants, the fertiliser value of the effluent is added as a benefit (House, 2010). Accurate monetary appraisal of this value is however difficult, as the fertilising value of digested sludge varies depending on the type of storage, the climate or the practices and techniques of usage. Estimates on the financial benefits of digested sludge used in agriculture (with the same output performance as with chemical fertilisers) can be obtained by assessing the costs of the substituted chemical fertilisers (Kossmann et al., undated).

Benefit of proper waste treatment
In developing countries, the most common practice for the disposal of municipal solid waste is landfilling. The organic fraction, which accounts for up to 70 % in the MSW, is seldom separated and recovered. By treating organic solid waste in AD plants, a large portion of the MSW can be diverted from the landfill, thus saving space and extending the lifespan of the landfill. These cost savings can also be monetised. Furthermore, savings in transport costs to the landfill can also be estimated.

In addition to these direct benefits, indirect benefits such as less environmental pollution and improved living conditions can also be taken into account. However, as it is difficult to express these externalities in monetary terms, this issue is not addressed further here.

6.2 Environmental aspects

Environmental aspects include consideration of the risks and benefits of an AD facility to the environment.

Reduction of firewood consumption and soil erosion

The use of AD systems and biogas plays a role in the global struggle against global warming. It reduces CO_2 emissions from burning fossil fuels in two ways. Firstly, biogas is a substitute for natural gas or coal when cooking, and for fossil fuels for heating, electricity generation and lighting. Secondly, use of effluent and digestate reduces the consumption of artificial fertiliser and thus avoids CO_2 emissions from fertiliser producing industries. Providing an alternative to firewood as a fuel source helps reduce deforestation and degradation of ecosystems as it sustains the capability of forests and woodlands to act as a carbon sink (Kossmann et al., undated).

Reduction of greenhouse effect

Methane is itself a greenhouse gas with a "greenhouse potential" 21 times higher than CO_2. Converting CH_4 to CO_2 (and water) through complete combustion is another way in which AD technology contributes to the mitigation of greenhouse gas emissions. This is however only valid in cases where the treated organic materials would otherwise undergo anaerobic decomposition thereby releasing methane to the atmosphere. Burning biogas also releases CO_2, but this only returns CO_2 which has been assimilated from the atmosphere by recently growing plants. There is therefore no net intake of CO_2 in the atmosphere from biogas burning as is the case when burning fossil fuels (Kossmann et al., undated).

It should be noted that transportation of materials needed for AD system construction, as well as feedstock for the AD system; and delivery of the AD products to the end-user may negatively affect the CO_2 balance.

Methane escape

As long as the AD facility is operated correctly and no methane loses occur, the high greenhouse gas potential of methane production is not a problem. Burning biogas converts methane into carbon dioxide and water. Under certain conditions however, where high feeding rates are combined with low consumption or limited gas storage, biogas may escape directly through the compensation tank into the environment. The installation of biogas lamps together with clear operating instructions for the households will help mitigate the risk of biogas overproduction and losses. In addition, installation of a pressure meter can inform households as to how much biogas is still available at the end of a day.

Ground water pollution

Biogas installations with leakages may result in slurry seeping into the subsurface. Also slurry pits, which are often not lined, may have the same effect. Although generally harmless, the discharge may pollute nearby water pits. Therefore, construction instructions should also specify a minimal distance between the AD installation and the closest water sources.

6.3 Socio-cultural aspects

Besides technical and financial aspects, which are normally automatically considered when developing a biogas project, socio-cultural aspects also have to be taken into account. Although this might be less obvious at first sight, it can be of utmost importance for the long-term operation and sustainability of the biogas plant.

An important principle of any biogas project should be to involve the persons concerned as early as possible in the planning process. Where biogas plants are operated at a household level, women should be included in the planning and decision-making process from the beginning. Women are generally the most affected by the new technology, especially if the gas is to be used for cooking (Picture 36). Furthermore, it is typically the woman of the household who is in charge of feeding the biogas plant. Experience shows that as women are more affected by malfunctioning of the plant, they are also more interested than men in ensuring it functions properly, through, for example, an efficient repair service (Kossmann et al., undated).

When promoting the use of biogas, many positive aspects are communicated such as a clean energy source, reduction of indoor air pollution and savings in time and money due to replacement of traditional cooking fuel by "free" biogas. However, people's habits are strongly affected when switching to biogas for cooking instead of using firewood, charcoal or LPG, be it at household or institutional level (e.g. canteens). It is therefore also important to make people aware of possible negative consequences of cooking with biogas such as:

- Using biogas requires longer cooking times as compared to charcoal or liquefied petroleum gas.
- Biogas cannot provide the strong heat required to prepare some meals.
- The residual heat of charcoal keeps the meal warm. This is not possible with biogas.
- Meals prepared with biogas do not taste the same as with charcoal.
- The amount of biogas available is limited per day. Normally, a second cooking fuel source is necessary to cover the daily need (Picture 37).

Picture 36: Indian woman cooking with biogas (photo: Sandec).

Picture 37: Indian kitchen with biogas stove on the left and LPG stove on the right hand side (photo: Sandec).

Acceptance of biogas and slurry from faeces

The acceptance of biogas also depends on ethical barriers or socio-cultural taboos. This is especially true regarding the use of biogas generated from human faeces or animal excrement. Many religions have very strict laws with regards to cleanliness, especially in connection with human and, to a lesser extent, animal excrement (Kossmann et al., undated).

In some cultures it is therefore not uncommon that people refuse to cook with biogas generated from faeces. Use of the effluent as fertiliser may also be problematic as it was shown in an example in South India, where the concentration of pathogens was too high to allow for unrestricted irrigation of crops (Estoppey, 2010). Sometimes, unexpected objections can occur, as illustrated in the following example from Tanzania:

Example from a student's canteen at a secondary school in Dar es Salaam:

In the beginning neither the project initiator nor the biogas company could understand the initial refusal to use biogas and its defamation by the cooks. Eventually it was discovered that this was caused by the fact that the cooks took charcoal from the school for their private consumption (which was still true) and feared the reduction in charcoal purchase by the school (Gyalpo, 2010).

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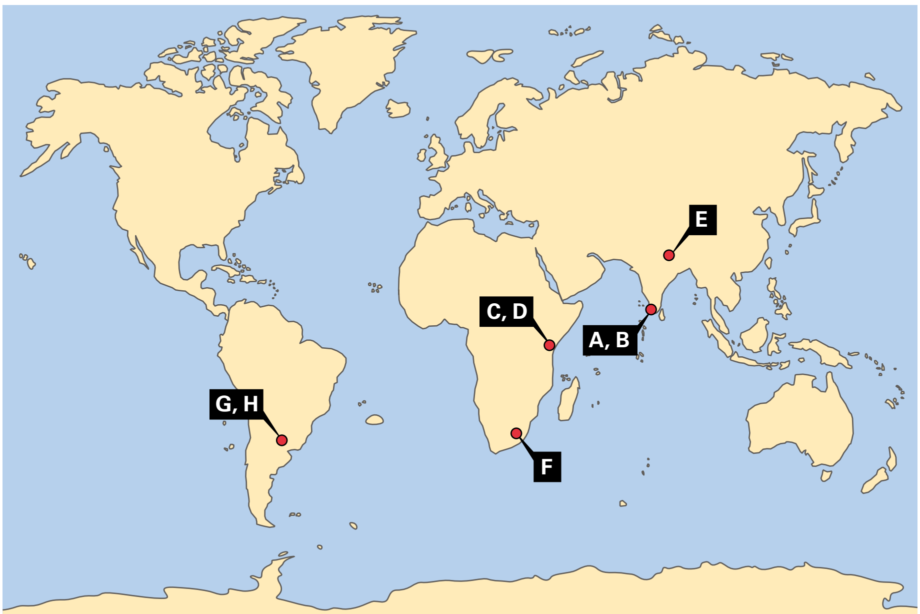
PART II: CASE STUDIES

The case studies presented in this part of the book are examples of small- to medium-scale biogas plants in developing countries that treat organic solid waste. Each case study contains a short technical description of the biogas plant, information on the typical feedstock used, gas production, biogas use, effluent quality, some social aspects, and economic considerations. The case studies are summarised in Table 1. Case studies A to F were evaluated by Sandec/Eawag while the data for case studies G to H have been derived from literature, key informants and/or the internet.



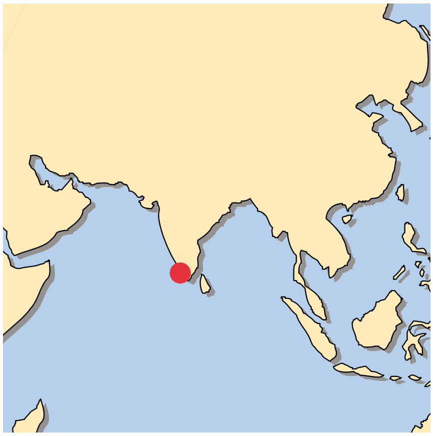
	Location	Digester Type	Digester Volume (Active Slurry Vol.)	Feedstock	Daily Load (wet weight)	Organic Loading Rate (OLR)	Daily Gas Production	Specific Gas Production (SGP)	Investment Costs (Cost per m^3 Digester)
			m^3	*Waste type*	*kg/d*	*kg VS/m³ d*	*m³/d*	*m³/kg VS d*	*US$*
A	Thiruvananthapuram, India	Floating drum	25 (21.3)	Market waste (mainly fish waste)	85.5	0.57	4.97	0.41	34 950 US$ (1 398 US$/m³)
B	Kumbalangi, Kochi, India	Floating drum	2 (1.46)	Kitchen waste	2.9 (+11.7 L waste H_2O)	0.41	0.68	1.15	593 US$ (296.5 US$/m³)
				Kitchen waste, Human feces	3.6 (+36.5 L waste H_2O)	0.58	0.69	0.81	
C	Dar es Salaam, Tanzania	Floating drum	1 (0.85)	Kitchen waste	2 (+18 L H_2O)	0.53	0.29*	0.64	420 US$ (420 US$/m³)
				Market waste	2 (+18 L H_2O)	0.17	0.13*	0.88	
D	Dar es Salaam, Tanzania	Floating drum	4 (3.4)	Canteen waste	8 (+60 L H_2O)	0.52	0.79*	0.45	2 135 US$ (534 US$/m³)
				Canteen waste	16 (+60 L H_2O)	1.12	1.56*	0.41	
E	Nepal	Fixed-dome	3*10 (7.5) 20 (15.3) 35 (24.9)	Human feces, partly kitchen waste	diverse	n/a	0.17–0.60	n/a	17 472 US$ (206 US$/m³)
F	Lesotho	Fixed-dome	6–19	Human feces, kitchen waste, pig & chicken manure	diverse	n/a	0.06–>1	n/a	500–3 000 US$** (83–667 US$/m³)
G	Gobernador Crespo, Santa Fe, Argentina	Floating drum	150	Domestic organic waste	550	n/a	55	n/a	117 895 US$ (786 US$/m³)
H	Emilia, Santa Fe, Argentina	Horizontal plug-flow	24.75	Domestic waste poultry manure pig manure canteen waste	100 (+450 L H_2O)	0.69	25	1.46	8 066 US$ (326 US$/m³)

Table 1: Overview of case studies.

* excluding loss through rim between gasholder and digester wall.
** including biogas digester, Anaerobic Baffled Reactor and Planted Gravel Filter.

A. Anaerobic Digestion of Market Waste in Thiruvan-anthapuram, South India

Project background and rationale



Thiruvananthapuram is the capital of the Indian state of Kerala. It is located on the west coast of India near the extreme south of the mainland. The waste from the markets is mostly dumped on open ground nearby while some wastes are also burned.

In 2000, the Ministry for Environment published the Municipal Solid Waste (Handling and Management) Rules 2000 (MSWR). These rules clearly assign the responsibility for solid waste management, particularly the development of infrastructure, to local government authorities. This involves collection, storage, segregation, transportation, processing, and disposal of municipal solid waste. The rules furthermore specify that all biodegradable wastes (fish, meat vegetable or slaughterhouses) shall not be landfilled but rather treated appropriately and used. However, neither the technology choice to achieve this nor any specific end-use is defined in the rules. To comply with these rules, several municipalities have decided to treat their organic waste in biogas plants. The plant of the Sreekaryiam Grama municipality was chosen for a monitoring and evaluation study by Eawag/Sandec in order to obtain more information on biogas plants treating market waste (Picture A2). The plant was constructed by a local company, BIOTECH, which up until 2009 had constructed 28 municipal biogas plants.

Feedstock

The feedstock of the Sreekaryiam biogas plant consists almost exclusively of fish waste (Picture A3). Some small quantities of vegetable and fruit wastes are added sporadically. The biggest fraction consists of fish innards (61 %), while the remainder consists mostly of fish flesh and skin tissue (11 %), heads (11 %), whole small fish (8 %), gills (6 %) and tails (3 %).

Picture A1: Fish market of Sreekaryiam Grama Panchayat, Thiruvananthapuram (photo: Sandec).

Picture A2: Floating drum biogas plant at Sreekaryiam fish market (photo: Sandec).

Picture A3: Typical feedstock of the Sreekaryiam biogas plant (photo: Sandec).

Picture A4: Inlet of Sreekaryiam biogas plant (photo: Sandec).

Picture A5: Grinding machine for big pieces (photo: Sandec).

Description of technology and design

Figure A1 shows a schematic diagram of a municipal biogas plant as designed by BIOTECH. It is a floating-drum plant with a slurry loop system.

- After pre-treatment with a grinder (Picture A5) the feedstock is fed into the inlet tank (Picture A4), from where it is then flushed into the main digester tank with a volume of 25 m^3 (active slurry volume 21.3 m^3).
- The digester is 3 meters deep and has a diameter of 3.4 meters. To increase the retention time for solids, there is a 1.5 meter high barrier inside the middle of the tank at right angles to the inflow and outflow direction.
- Opposite the inlet is the outlet where the digestate (slurry) flows into the effluent tank. From here effluent and slurry are pumped into the overhead storage tank. The pump is operated with electricity from biogas. The slurry in the overhead tank is used to flush the feedstock from the inlet tank into the digester tank. With this slurry loop design, no fresh water is used to dilute and flush the waste into the digester tank. Fresh water is needed only for cleaning purposes.
- Excess slurry leaves the system through an overflow from the effluent tank into a nearby drain. The gas that is produced is stored in the gasholder drum. This drum floats in a water jacket to prevent methane losses. The up and down movement of the drum is stabilised by a guide pole in the middle of the reactor.
- A pipe connects the gasholder drum to a biogas scrubber that reduces the content of corrosive hydrogen sulphide in the biogas.

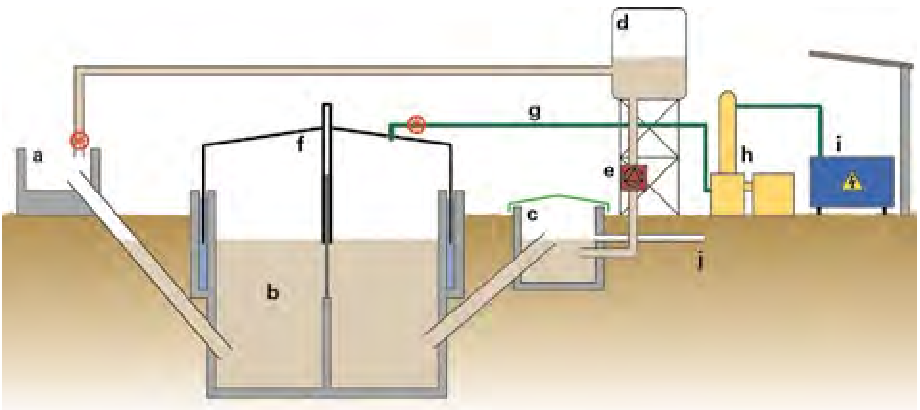


Figure A1: Schematic plan of a BIOTECH municipal biogas plant.
a) Inlet tank for feedstock, b) Digester tank, c) Effluent tank, d) Effluent storage tank, e) Effluent pump, f) Gasholder drum. The drum is stabilised by a guide pole in the middle and is floating in a water jacket outside the digester, g) Biogas pipe, h) Gas scrubber, i) Biogas generator, j) Drainage connection for excess effluent.

Input and operational parameters

Table A1 lists the input characteristics of the Sreekaryiam market-scale plant. While the digester feeding capacity is 250 kg/day, the actual average load is 85.5 kg per day, thereby far below this maximum load. The AD plant is operated using a slurry loop design where no fresh water is used to dilute the feedstock. Instead slurry from the outlet is used to flush fresh feedstock into the digester passing by an "effluent storage tank" (d in Figure A1). Table A2 presents the main operational parameters.

Parameter	Average Value
Daily feed (kg wet weight/d)	85.5
Water added (L/d)	0
TS (% of raw waste)	23
VS (% of TS)	63
COD (g O_2/g TS)	1.31

Table A1: Feedstock characteristics of the Sreekaryiam biogas plant.

Parameter	Average Value
OLR (kg VS/m^3 d)	0.57
HRT (d)	249
T (°C)	29.3
pH	7.85

Table A2: Operational parameters of the Sreekaryiam biogas plant. The approximation 1 kg substrate (wet weight) = 1 L is used for calculation of HRT.

The combination of the low feeding load and the absence of added fresh water leads to a very high Hydraulic Retention Time (HRT) of over eight months.

Gas production

Table A3 shows the gas production and composition as measured on the market plant over a period of 2 months.

Parameter	Average Value over 2 Months
Daily gas production (m^3/d)	4.97
GPR (m^3/m^3 digester d)	0.233
SGP (m^3/kg VS)	0.41
Average CH_4 content (%)	66.8
Average CO_2 content (%)	27.4

Table A3: Gas production and composition of Sreekaryiam market-scale plant.

Use of biogas

The biogas is scrubbed in a packed column where the gas flows upwards and water containing iron salts flows downward (counter-current flow). Hydrogen sulphide in the biogas is dissolved in the water and oxidised. After scrubbing, the biogas is used in a special 5 kW biogas generator to produce electricity. The electricity is used to light the market and the surrounding streets (Picture A6). However, as the average daily gas production of 4.97 m^3 is a bit higher than the electricity demand from lighting, the excess biogas is occasionally flared.

Picture A6: Biogas lamp for street lighting (photo: Sandec).

Quality and use of the effluent

The effluent of the Sreekaryiam market-scale plant is liquid, dark and homogeneous (Picture A7).


Picture A7: Effluent tank at the Sreekaryian biogas plant (photo: Sandec).

The characteristics of the effluent are shown in Table A4. Most solids remaining in the effluent are dissolved. The COD and VS values show that there is still a considerable amount or organic matter left in the effluent despite the HRT of over eight months.

The total nitrogen, ammonium, total phosphorous and ortho-phosphate values of the effluent are high. Although high ortho-phosphate values do not create problems for anaerobic digestion, the high ammonia values can be critical for the biological process. The high nitrogen concentration has not caused serious inhibition of methane production, however if an increase in ammonia production persists, inhibitory effects may occur. Furthermore, the ammonia smell could negatively affect general acceptance of the biogas plant.

Parameter	Average Value
TS (%)	0.97
VS (% of TS)	76.9
COD (g O_2/L)	9.0
N_{tot} (g N/L)	7.52
NH_4-N (g N/L)	6.10
P_{tot} (g P/L)	0.55
PO_4-P (g P/L)	0.49
Alkalinity (g $CaCO_3$/L)	27.78
pH	7.85

Table A4: Characteristics of the effluent of the Sreekaryiam biogas plant.

The effluent of the digester is not used as fertiliser. It is pumped into the storage tank and from there used to flush the feedstock into the digester. Excess slurry is discharged from the effluent tank into the drain.

Costs

Table A5 shows the average costs for construction, operation, and maintenance of a municipal biogas plant. The investment costs are substantial. The annual costs for operation and maintenance add up to 15 % of the investment costs.

Investment Costs		
Material	600 000 INR	13 980 US$
Labor	900 000 INR	20 970 US$
Total investment costs	**1 500 000 INR**	**34 950 US$**
Operational and Maintenance Costs		
Annual operation expenses	112 500 INR	2 621 US$
Annual maintenance contract	75 000 – 112 500 INR	1 748 – 2 650 US$

Table A5: Average costs of a municipal biogas plant (100 INR = 2.33 US$ as of August 2008).

Practical experience and lessons learned

Although some technical challenges remain because of the high proportion of nitrogen-rich fish waste in the feedstock, this plant is considered ideal for the treatment of market waste. Counter-measures need to be implemented because of the high nitrogen content which can lead to inhibitory effects. These include:

- Adding fresh water. As operators of the plant want to remain independent from fresh water sources, addition of fresh water is only a theoretical option.
- Adding more high-carbon waste, such as vegetable and fruit waste. This would increase the C:N ratio of the feedstock (which is currently about 4) closer to the recommended value of 20.

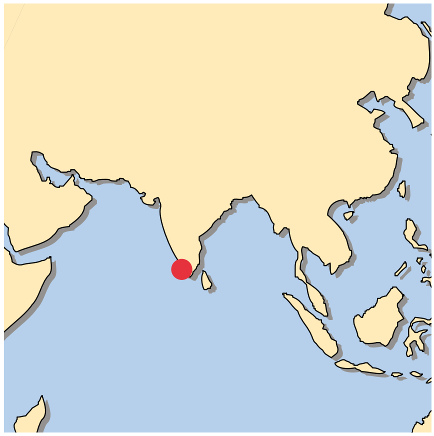
One main disadvantage of such biogas plants for market wastes are the large investment and high annual operating costs. Although these plants can ensure proper waste treatment they do not generate direct monetary benefit. Therefore financial incentives for the municipality to invest and operate such plants are lacking. It seems that the most challenging task is to find ways to create economical attractiveness for a such project. Possible solutions are: (i) the reduction of the investment costs; (ii) increasing revenues by selling the effluent as fertiliser; or (iii) the development of CDM projects and use of funding from sales of CERs to cover some of the costs.

References

Heeb F. (2009). Decentralised anaerobic digestion of market waste. Case study in Thiruvananthapuram, India. Swiss Federal Institute of Aquatic Science and Technology (Eawag). Dübendorf, Switzerland.

B. Co-Digestion of Kitchen Waste and Human Faeces in Kumbalangi, South India

Project background and rationale



The state of Kerala is located at the south-western tip of India. A unique initiative to enhance local income through tourism transformed the tiny island of Kumbalangi. The "Kumbalangi Integrated Tourism Village Project" was initiated to establish a sustainable approach for the management of local ecological resources such as fish and mangroves.

One goal of this initiative was to improve the sanitary situation on Kumbalangi Island and to replace the commonly used "hanging toilets" and other substandard toilet facilities. These toilets discharge excreta and wastewater directly into surface waters thus polluting the backwaters (Picture B1 and B2). The idyllic landscape is also threatened by the lack of solid waste management collection services. Waste is dumped indiscriminately, burnt in household gardens or littered directly into the backwaters.

Picture B1: Hanging toilets (photo: Sandec).

Picture B2: Toilet discharging into backwaters (photo: Sandec).

In order to reduce the environmental problems caused by the lack of appropriate sanitation infrastructure and municipal solid waste management, the local Kerala based NGO BIOTECH assisted the community to improve 150 toilets by linking them to biogas digesters. A further 650 digesters were designed and installed to use excreta and wastewater as well as food waste from kitchens as feedstock.

In collaboration with BIOTECH, Eawag/Sandec conducted an assessment of selected household-scale plants in 2010. The technical assessment evaluated two types of reactor operation; one fed only with organic solid waste (called: Food Waste Biogas Plant) and the other fed with food waste and toilet waste (called: Toilet Linked Biogas Plant).

Feedstock

Plant 1 (Food Waste Biogas Plant)
The feedstock of plant 1 is from two families, the ones owning the plant (4 adults & 2 children) and their neighbours (2 adults & 2 children).

On "usual" week days the feedstock amounts to about 2 kg of kitchen waste (mainly rice leftovers and slaughtered chicken waste). On Sundays an additional 6.7 kg of chicken waste are typically also added (Picture B3).

Picture B3: Left: Typical feedstock of plant 1 on "usual" days; Right: Big quantities of chicken waste (legs, heads, stomachs and blood) fed on Sundays and celebration days (photo: Sandec).

The average feed of the plant was thus 2.9 kg/day of solid waste with an additional 11.7 litres of liquid waste (mainly organic wastewater from the kitchen such as rice cleaning and cooking water).

Plant 2 (Toilet Linked Biogas Plant)
Plant 2 is a Toilet Linked Biogas Plant (TLBP) owned and operated by one family (2 adults & 2 young adults). An average of 3.6 kg solid waste (mainly rice leftovers and faeces) and 36.5 litres of liquid waste (mainly flushing water and organic wastewater from the kitchen) are added to the digester daily.

Description of technology and design

The plants are floating-drum digesters as shown in Figure B1. The main components of the design are:

- The digester tank material is constructed from prefabricated Reinforced Cement Concrete (RCC) slabs fitted together in an excavated pit. The digester has an external diameter of 1.4 m and is 1.6 m deep.
- The gas holder is constructed out of Fibreglass Reinforced Plastic (FRP) and has a diameter of 1.2 m and a height of 1.1 m.
- The inlet for food waste and the effluent outlet both consist of square chambers (0.45 m x 0.45 m) made of bricks which are linked to the digester by a pipe at an angle of about 45°.
- The inlet for toilet waste consist of a manhole constructed out of cement or brick, which is connected by pipes, at one end, to the latrines and at the other, to the digester (Picture B4).

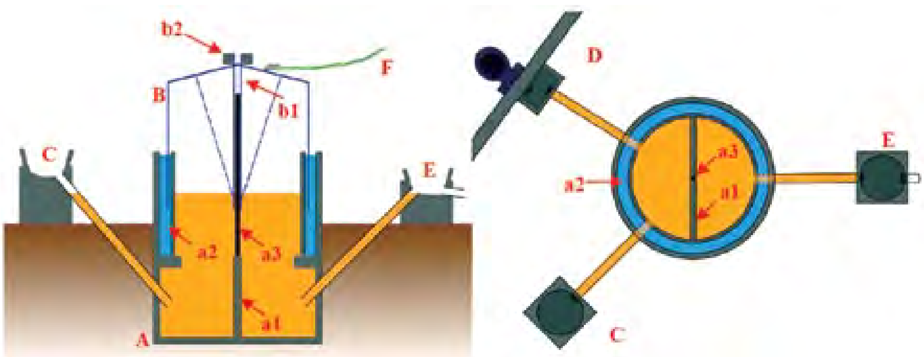


Figure B1: Cross section and top view of a 2 m³ toilet linked plant installed in Kumbalanghi.
A) digester tank, a1) orthogonal barrier, a2) water jacket, a3) metallic central axe, B) gasholder drum, b1) central tube, b2) 20 kg stone, C) food waste inlet, D) toilet waste inlet, E) effluent outlet, F) biogas outlet.

Picture B4: Toilet connected to biogas plant (photo: Sandec).

Picture B5: Newer model made completely out of Fibreglass Reinforced Plastic (FRP) (photo: Sandec).

Input and operational parameters

Table B1 lists the (diluted) influent characteristics and Table B2 the operational parameters of the two plants.

Parameter	Plant 1 Food Waste Biogas Plant	Plant 2 Toilet Linked Biogas Plant (TLBP)
Daily feed (kg wet weight/d)	2.9	3.6
Wastewater added (L/d)	11.7	36.5
TS influent (%)	4.5	2.7
VS (% of TS)	88.9	88.5
COD_{tot} (g O_2/L)	69.6	24.6
COD_{tot} (g O_2/g TS)	1.54	0.91
COD_{diss} (% COD_{tot})	24.7	35.8

Table B1: Characteristics of influent (diluted feedstock) for the plants in Kumbalangi.

Parameter	Plant 1 Food Waste Biogas Plant	Plant 2 Toilet Linked Biogas Plant (TLBP)
OLR (kg VS/m^3 d)	0.41	0.58
HRT (d)	100	37
T (°C)	28.5	29.4
pH	7.4	6.9

Table B2: Operational parameters of the plants in Kumbalangi. The approximation 1 kg substrate (wet weight) = 1 L is used for calculation of HRT.

Gas production

Table B3 shows the gas production and composition of the two plants measured over a period of 5 weeks.

Parameter	Plant 1 Food Waste Biogas Plant	Plant 2 Toilet Linked Biogas Plant
Daily gas production (m^3/d)	0.68	0.69
GPR (m^3/m^3 digester d)	0.47	0.47
SGP (m^3/kg VS)	1.15	0.81
Average CH_4 content (%)*	65	61
Average CO_2 content (%)	35	39

* CO_2 content was measured with BRIGON-CO_2 Indicator. 100%-% CO_2 = Max. % CH_4.

Table B3: Gas production and composition of plant 1 and 2 over a period of 5 weeks.

Use of biogas

The biogas produced is used by the families for cooking, and on average, for more than 3 hours of cooking time can be achieved. The families still use an additional cooking fuel when they need to cook more quickly and more than one stove is used.

Quality and use of the effluent

The two plants produce a liquid effluent with less than 1 % TS. The nutrient content in the effluent is similar for both plants, with a rather high content of nitrogen and potassium compared to phosphorus. However, it is difficult to evaluate the fertilising value as this is dependent on the quality of the soil and type of crops where the fertiliser is applied. The values of the different parameters which characterise the effluent are given in Table B4.

The Toilet Linked Biogas Plant shows substantial reduction in pathogen content in the effluent, but the concentration of E. Coli and Total Coliforms only allows restricted irrigation according to the WHO-guidelines for "safe use of wastewater, excreta and greywater". The effluent should be applied directly on the roots and should not be spread on top of the vegetables. In addition, contact with mouth or wounds should be avoided and hands must be washed after handling of the effluent. Currently the effluent is discharged into the surface waters, thereby contributing to pollution and eutrophication of the backwaters. This effluent could however be suitable for the irrigation of banana and coconut trees.

Parameter	Plant 1 Food Waste Biogas Plant	Plant 2 Toilet Linked Biogas Plant (TLBP)
TS (%)	0.62	0.5
VS (% of TS)	64.7	63.4
COD_{tot} (g O_2/L)	6.2	3.8
COD_{tot} (g O_2/g TS)	1.01	0.77
COD_{diss} (% COD_{tot})	21.5	11.7
N_{tot} (g N/L)	2.2	8.7
NH_4-N (g N/L)	1.41	0.40
NH_4-N (% N_{tot})	63.0	48.1
P_{tot} (g P/L)	0.078	0.061
K_{tot} (g K/L)	2.54	0.77

Table B4: Characteristics of the effluent.

System performance

The monitoring of the food waste biogas plant and the Toilet Linked Biogas Plant showed that both plants are working satisfactorily in terms of technical performance.

Costs

Table B5 lists the different costs, the subsidies and finally the amount a family has to pay to acquire an ordinary 2 m^3 Toilet Linked Biogas Plant. Due to considerable changes in costs and availability of subsidies between 2006 and 2010, figures are given for both periods. The price for the infrastructure (plant) increased due to a change in materials - previously the digester was made out of Reinforced Cement Concrete (RCC) but since 2010 Fibreglass Reinforced Plastic (FRP) (Pictures B4 and B5) is used.

Toilet Linked Biogas Plant 2 m³		2005–2006 (INR)	2010 (INR)
Costs	Plant	22 700	33 000
	Labour charge	3 400*	1 000**
	Stove + pipe	included	1 000
	Latrines	included	not included
	Total (INR)	**26 100**	**35 000**
Subsidies	Kerala government	16 000	-
	Central government	2 700	8 000
	Kumbalanghi Panchayat	63.0	48.1
	Total (INR)	**27 000**	**8 000**
Paid by the Customer	**Total (INR)**	**5 400**	**27 000**
	Total (US$)	**119**	**593**

* Average values calculated from the information obtained from 27 visited families.
** Estimates given by the director regarding the present price for the transport, the excavation of a pit and the cow dung.

Table B5: Costs, subsidies and final amount paid by the customers in the years 2005–2006 and in the year 2010 (100 INR = 2.2 US$, rate as of January 2010).

Social aspects

A household survey showed that the overall acceptance of the biogas system was good and that most families would recommend it to others. Improved waste management and the production of biogas were mentioned as the main advantages. The main disadvantages stated were: (a) the smell of the effluent (when using toilet waste), (b) not enough biogas, (c) slower cooking times with biogas and (d) the difficult access and design of the toilet facilities (steep and unsafe stairs). Only one family objected to using biogas for cooking because it was produced from excreta. Knowledge on how to operate and maintain the system was found to be lacking.

Practical experience and lessons learned

In general, these systems are suitable for the treatment of kitchen and toilet waste, and both plants are working satisfactorily in terms of technical performance. However, the survey revealed that several families discharge the effluent directly into the backwaters. The values of COD and N in the effluent far exceed the environmental standards for discharge of environmental pollutants given by the Ministry of Environment & Forests (Government of India). Therefore this practice should definitely be avoided.

As the quality of the effluent does not meet the requirements for use as a fertiliser or for discharging into receiving water bodies, a post-treatment step, such as a filter bed, is needed. The low concentration of total solids in the effluent indicates that more food waste could be added as feedstock without impairing the digester activity. This would increase the gas yield. However, this would require additional effort for the families to collect more food waste from neighbouring households as this would exceed their own daily waste generation.

The main barrier for widespread replication of these systems is the high investment costs and the risk of pollution by discharged effluent. The current investment cost for these biogas reactors are not affordable based on an average family income on Kumbalangi Island. With the current subsidy system and the current design and construction cost, the payback period is 15 years.

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C. Anaerobic Digestion of Kitchen Waste in Dar es Salaam, Tanzania

Project background and rationale

The city of Dar es Salaam is the administrative, commercial and industrial centre in Tanzania. The majority of the waste generated by households in the city is either self-disposed close to the site where it was produced or illegally dumped at the roadside, in open spaces or in drains. Kitchen waste amounts to about 42 % of the household waste and is a potentially valuable source for the production of biogas.

Picture C1: ARTI biogas plant (photo: Sandec).

The Indian organisation, Appropriate Rural Technology Institute (ARTI), developed a small-scale biogas system in 2003 designed for use at household level (see Picture C1). The design and development of this technology which uses organic solid waste rather than manure as feedstock won the 'Ashden Award for Sustainable Energy' in 2006. About 2500 of these biogas plants have been in use in Maharashtra, India since 2007. The ARTI branch in Tanzania (ARTI-TZ) started implementing these systems in East Africa in November 2006: Around 31 ARTI Compact Biogas Systems (CBS) have been installed in Tanzania and Uganda up until November 2008. An ARTI biogas research plant was installed and operated at the campus of Ardhi University in Dar es Salaam in order to obtain reliable information on this low-tech biogas system. A detailed monitoring of this plant was conducted by Eawag/Sandec in collaboration with Ardhi University.

Feedstock

Organic household waste in Dar es Salaam consists mainly of kitchen waste comprised of food leftovers and peelings/pieces of vegetables and/or fruits. In the research plant at the university two different substrates were tested: Food waste (TS: 24 %, VS: 91 %) and market waste containing vegetables and fruits (TS: 10 %, VS: 88 %) (Picture C2).

Picture C2: Food waste (left) and market waste (right) (photo: Sandec).

Food waste was collected from the student's canteen at Ardhi University and fruit and vegetable waste was obtained from Mwenge market. All waste materials were chopped and mixed with water (1:9 ratio) before being fed to the digester.

During the start-up period, the biogas plant was inoculated with 60 kg of dried cow dung mixed with water and 300 L effluent from an existing biogas plant. The biogas plant was then fed with 2 kg/day canteen waste for four weeks, followed by 2 kg/day market waste for another four weeks. The daily load of 2 kg waste was based on literature findings and represents a realistic figure of waste quantity generated per Tanzanian household of 5 members (Kaseva & Mbuligwe, 2005). After a break of one week without feeding, the rate of feeding of both substrates (canteen and market waste) was then increased from 2 to 5 kg/day.

Description of technology and design

The ARTI compact biogas system is made out of two standard high-density polyethylene water tanks and standard plumber piping. The top is cut off of both water tanks. The larger tank acts as the digester while the smaller one is inverted and inserted into this larger one. This smaller inverted tank is the floating gas holder, and rises proportionally to the gas produced and acts as a storage space for the gas (Figure C1).

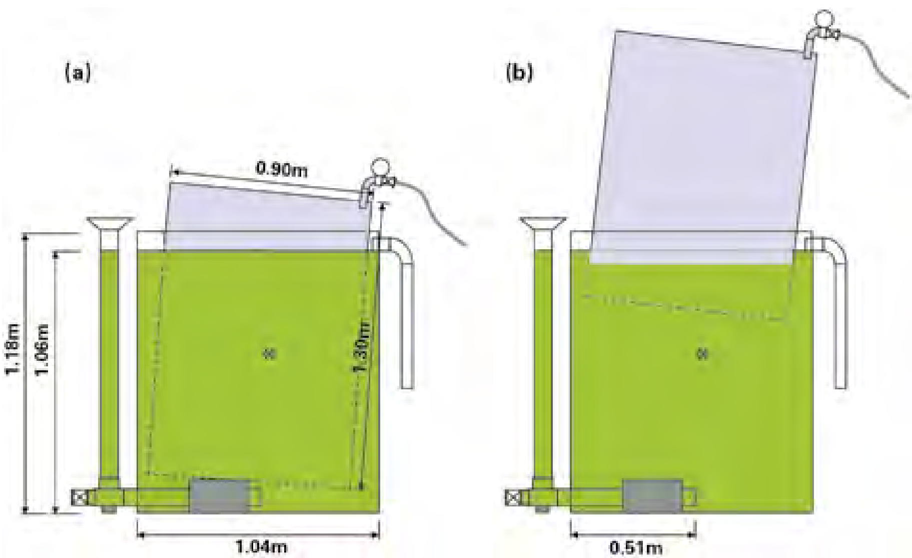

Figure C1: ARTI compact biogas plant scheme ((a) gasholder empty, (b) gas-filled).

Input and operational parameters

This compact household biogas system (approximately 1 m^3 capacity) is designed for treating 1–2 kg (dry weight) of kitchen waste per day, and requires a space of about 2 m^3 and 2.5 m in height. The effective volume of the digester is 0.85 m^3, given by the dimension of the 1 m^3 water tank (inner radius: 0.5 m) and the position of the overflow-pipe (1 m above ground level). The usable gas volume of the 0.75 m^3 gasholder is 0.4 m^3. The Hydraulic Retention Time (HRT) suggested by ARTI-TZ is 42 days.

Table C1 lists the characteristics of the two feedstocks (kitchen waste and market waste) after dilution with fresh water.

Parameter	Feedstock 1 (Kitchen Waste)	Feedstock 2 (Market Waste)
Daily feed (kg wet weight/d)	2	2
Water added (L/d)	18	18
TS (%)	2.7	0.8
VS (% of TS)	94	87
COD_{tot} (g O_2/L)	28.3	7.6
COD_{tot} (g O_2/g TS)	1.05	0.95
COD_{diss} (% COD_{tot})	28.6	56.6

Table C1: Characteristics of influent (diluted feedstock).

Table C2 shows the main operational parameters of the ARTI-biogas plants fed with both feedstocks.

Parameter	Feedstock 1 (Kitchen Waste)	Feedstock 2 (Market Waste)
OLR (kg VS/m^3 d)	0.53	0.17
HRT (d)	42.5	42.5
T (°C)	28.8	28.8
pH	6.5	6.5

Table C2: Operational parameters of household plants in Dar es Salaam. The approximation 1 kg substrate (wet weight) = 1 L is used for calculation of HRT.

Gas production

The gas production rate from food waste was observed to be approximately twice that from market waste (Table C3). Assuming that in Tanzania a household produces 1 kg of food leftovers and 1 kg of fruit and vegetable peelings per day, this 2 kg of kitchen waste should be able to generate roughly 170 L of biogas per day.

Parameter	Feedstock 1 (Kitchen Waste)	Feedstock 2 (Market Waste)
Daily gas production (m^3/d)	0.289	0.126
GPR (m^3/m^3 digester d)	0.34	0.15
SGP (m^3/kg VS)	0.64	0.88
Average CH_4 content (%)	56.8	66.4
Average CO_2 content (%)	41.7	33.2

Table C3: Gas production and composition of ARTI research plant in Dar es Salaam.

Figure C2 presents the trend in daily gas production during the period when daily feeding was increased from 2 to 5 kg for both market and food waste. Between feeding market waste and food waste, a 3-day feeding break was effected in which the gas production dropped to 70 L/day.

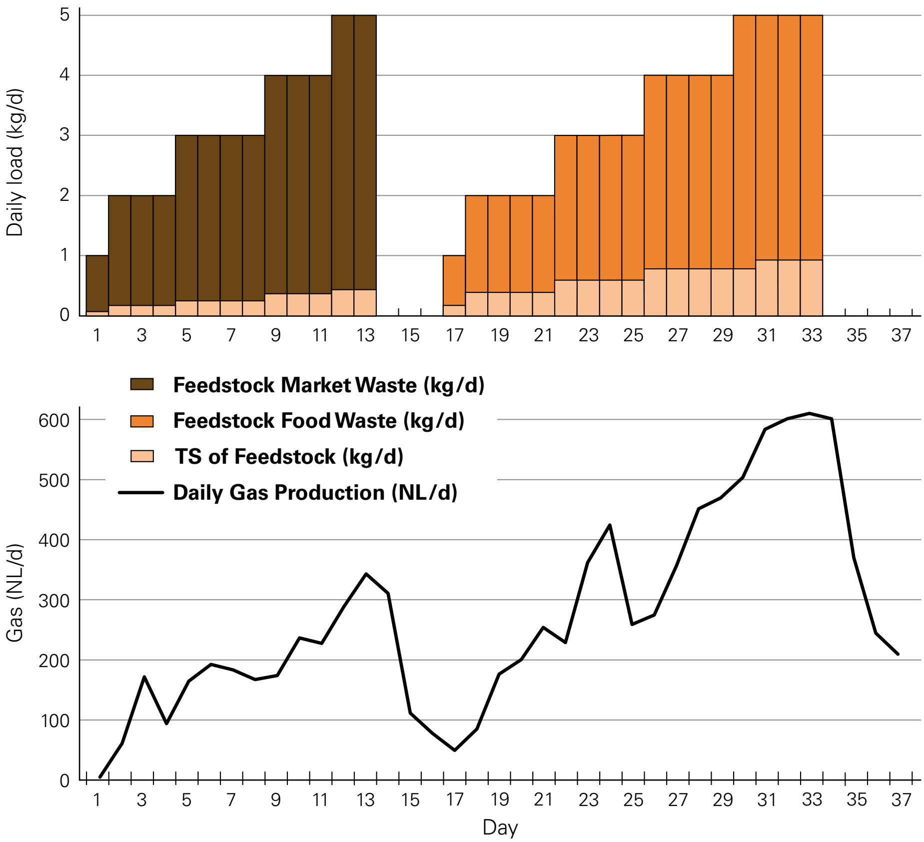

Figure C2: Varying daily feed and resulting gas production.

Use of biogas

The 170 L of biogas produced per day is equivalent to a 45-minutes burning period. This burning period represents about a third of the average cooking time of 2.5 h per day for a household with five members. Since this is an experimental facility the gas was not used for productive purposes but flared.

Quality and use of the effluent

Table C4 presents the effluent characteristics of the ARTI research plant in Dar es Salaam using both feedstocks. The average concentration of total phosphorus in the effluent when feeding food waste was 0.248 g/L (6.8 % of TS), of which 69 % was in the form of phosphate. When feeding market waste, the effluent had a total phosphorus concentration of 0.225 g/L (8.2 % of TS), of which 66 % was phosphate.

While average ammonium-nitrogen concentration in the inflow was found to be 0.032 g/L for food waste and 0.028 g/L for market waste, the average ammonium-nitrogen concentration observed in the effluent was 0.074 g/L for food waste and 0.086 g/L for market waste. Therefore, the bacterial activity resulted in an ammonium-nitrogen increase of 134.5 % for food waste, and 206.5 % for market waste.

The quality of the effluent as organic fertiliser can only be judged on the basis of its suitability to support the growth of a particular type of plant. Furthermore, the concentration of potassium (K), as well as that of Fe, Ca, Mg and Zn is of vital interest because phosphate builds chelates with these essential trace elements, which can potentially prevent the uptake of PO_4 by the plants. In this case study the effluent was not used and was discharged into a drain leading to the sewer of the university.

Comparing effluent characteristics to quality standards for compost is also of limited validity. Nevertheless, analyses show that the concentrations of heavy metals in the effluent were far below the tolerated values for compost. This result was however not unexpected as the canteen and market wastes are not likely sources of heavy metals.

Parameter	Plant 1 (Food Waste)	Plant 2 (Food and Human Waste)
TS (%)	0.4	0.3
VS (% of TS)	47	47
COD_{tot} (g O_2/L)	4.8	1.2
COD_{diss} (% COD_{tot})	43.8	58.7
N_{tot} (g N/L)	0.15	0.19
NH_4-N (g N/L)	0.074	0.086
NH_4-N (% N_{tot})	49	45
P_{tot} (g P/L)	0.248	0.225

Table C4: Characteristics of the effluent.

System performance

The research plant did not experience noticeable problems and was regarded as simple to operate. The most important technical improvement recommended concerned the digester tank and respective gasholder tank size. The current design leads to a gas loss of about 22 % due to the excessive space between the digester and gasholder. These two system components do not fit optimally as the design depends on the type and availability of different sized water tanks. Minimising the space between these two system components (tanks) would considerably reduce atmospheric loss of biogas.

An inspection tour where 12 owners of an ARTI biogas plant were visited clearly proved that a proper follow-up service is essential. Of the plants visited, 8 were not operational due to breakage and blockage of the inlet pipe, overfeeding, and damage to the gas tap. Following this survey, ARTI-TZ has made great efforts to improve its service and is now distributing a manual in English and Kiswahili to customers. A follow-up service is especially important during the first 3 months after installation of the biogas plant, since during this period the owners do not have enough experience with the basics of operating and maintaining the system.

Costs

The price of 850 000 TZS (420 US$) for a household ARTI biogas system is the main barrier to wide distribution of this technology in Tanzania. However, the payback period is low; estimated to be roughly three years based on an average household saving of around 336 kg charcoal per year - equivalent to 276 000 TZS (136 US$). With additional logistical and operational efforts, the daily feeding rate could gradually be increased from 2 to 5 kg, to produce 0.67 m^3/d of gas or 150 minutes of cooking time. Consequently, all cooking fuel could be replaced by biogas and the payback period would drop to only one year.

Social aspects

Since waste separation is not common practice in many developing countries, emphasis should be given to detailed explanations and examples, illustrating the different kinds of wastes and their suitability as feedstock. It is further recommended that the operational instructions are given not only to the owner of the biogas plant, but also to the person responsible for the daily feeding (maid, caretaker, etc.). It is important to note that for any new technology which requires a change in daily habits, the benefits need to convince its customers from the start, regardless of the society or culture.

Practical experience and lessons learned

The results of the study have revealed that there is a great potential for anaerobic digestion of the organic fraction of municipal solid waste in low- and middle-income countries. The ARTI system has proved to be effective in terms of the reduction of waste volume and organic load. Although the performance of the system in terms of gas production is good, the design of digester can and has to be improved. Operation and maintenance services are needed to ensure long-term and sustainable use of the system. High investment costs are considered to be the main barrier for wide implementation of the ARTI technology.

ARTI-TZ phased out their biogas program in 2012. This decision was taken because ARTI-TZ's biogas sector was not profitable while, at the same time, the maintenance activities were becoming more and more labour intensive and costly. The phasing out also had to do with the company SimGas entering the market in 2012. Apart from a modular manure-based system ("GesiShamba"), SimGas has developed improved urban biogas systems ("GesiSafi") that are based on the ARTI-principle and available in three sizes (550L, 2000L and 3500 L), but at lower costs. The digester elements, made of Polyethylene, are manufactured in Tanzania and distributed in the East African region. Since the start of its operations in 2012, SimGas has sold around 1000 of these systems.

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D. Anaerobic Digestion of Canteen Waste at a Secondary School in Dar es Salaam, Tanzania

Project background and rationale

The ARTI compact biogas system presented in case study C can be adapted for different sizes, depending on the dimensions of the water tanks commercially available. This also makes the system suitable for institutions like schools, hotels and orphanages. By 2010, 6 institutions in Dar es Salaam had installed an ARTI biogas plant, among them the Azania Secondary School with 110 boarding students. The installation was financed by the Tanzania Commission of Science and Technology (Costech) with the aim of promoting biogas technology on an institutional level. In 2010, the biogas system was monitored and evaluated by Eawag/Sandec in order to learn more about the suitability of the ARTI technology on an institutional scale.

Feedstock

Food waste from the students' canteen, which was previously dumped on the school premises, served as feedstock for the biogas plant. The typical local dishes are ugali (maize porridge), beans and makande (bean stew). Organic waste from food preparation (i.e. onion peeling, tomatoes and cabbage) and fruit peelings (bananas, mango) were not used as feedstock because, according to the kitchen staff, no instruments to cut the waste into small pieces were available. The amount of food waste fluctuates depending on the menu. On days without rice, the average food waste generated was 41 kg/day whereas on other days approximately 21 kg/day was available. This results in a mean food waste generation of 32 kg/day (TS: 26 %, VS: 92 %). On an irregular basis, children from outside the school came to collect food waste in a bucket for their animals, thus removing about 20 kg food waste. This caused a lack of feedstock on those days.

Description of technology and design

A detailed description of the ARTI compact biogas plant was presented in case study C (Picture C1).

Picture D1 shows the ARTI compact biogas system at Azania Secondary School which consists of three digester tanks of 4 m^3 in size. The size of the gas holder is 3 m^3. The three digesters work independently and are not connected to each other. ARTI recommends that 8 kg/day organic waste (wet weight) is fed into each tank and they are thus operated in parallel.

Input and operational parameters

Two of the three digesters were used for research during a period of 3 months in 2009/10. Digester 1 was fed with 8 kg canteen waste per day and digester 2 with 16 kg/d. The specific characteristics of the diluted feedstock in both digesters are listed in more detail in Table D1.

Picture D1: ARTI biogas plant at Azania Secondary School (photo: Sandec).

Parameter	Digester 1	Digester 2
Daily feed (kg wet weight/d)	8	16
Water added (L/d)	60	60
TS (%)	2.7	5.3
VS (% of TS)	95.7	94.8
COD_{tot} (g O_2/L)	54.1	121.1

Table D1: Characteristics of influent (diluted feedstock).

The main operational parameters of the digesters at the school in Dar es Salaam are presented in Table D2.

Parameter	Digester 1	Digester 2
OLR (kg VS/m^3 d)	0.52	1.12
HRT (d)	50	45
T (°C)	28.8	28.9
pH	7.2	7.1

Table D2: Operational parameters of institutional digesters in Dar es Salaam. The approximation 1 kg substrate (wet weight) = 1 L is used for calculation of HRT.

Gas production

Gas production was measured at different times each day and extrapolated in order to get a 24 h gas production rate. The mean values and the corresponding measured gas production based on the different input loads are shown in Table D3.

Parameter	Digester 1 (8 kg/d waste)	Digester 2 (16 kg/d waste)
Daily gas production (m^3/d)	0.791	1.557
GPR (m^3/m^3 digester d)	0.233	0.458
SGP (m^3/kg VS)	0.45	0.41
Average CH_4 content (%)	58	55
Average CO_2 content (%)	42	45

Table D3: Gas production and composition of digesters at the school in Dar es Salaam.

Similar to the household system described in case study C, the two gas holders and the digester tank do not fit well into each other. This leads to a gas loss of 17.5 %. Minimising this gas loss by improving the systems' design is of utmost importance. The mean biogas production excluding the losses through the rim was measured as 0.426 m^3/kg VS, while when including the loss to the atmosphere, gas yield is estimated at 0.516 m^3/kg VS.

Use of biogas

At Azania Secondary School, biogas is used for cooking in the canteen kitchen. Interviews with the cooks revealed that they appreciate biogas and consider it as a clean energy source. However, they also claim that it takes too long to cook with biogas and that there is an insufficient supply. Consequently, they have to switch from biogas to charcoal and therefore still prefer charcoal. It was also argued that some meals need to be prepared with strong heat that biogas cannot provide. Finally they also mentioned that some meals prepared with biogas do not taste as good as when cooked with charcoal. They report that cooking with biogas is suitable for preparing lunch whereas dinner should be prepared on charcoal. The residual heat of charcoal keeps the dinner warm for a longer period of time which is not possible with biogas.

Quality and use of the effluent

Due to the bacterial decomposition of organic waste, nutrients such as ammonium (NH_4^+) and phosphate (PO_4^{3-}) are present in the effluent. The effluent was enriched with these nutrients and can therefore be used as fertiliser. In the Azania Secondary School, part of the effluent was recycled and used to dilute fresh feedstock. Occasionally a small amount of the effluent was used to water the nearby plants on the campus. Table D4 shows the characteristics of the effluent.

Parameter	**Digester 1** (8 kg/d waste)	**Digester 2** (16 kg/d waste)
TS (%)	0.33	0.42
VS (% of TS)	47.7	55.6
COD_{tot} (g O_2/L)	2.8	1.52
COD_{tot} (g O_2/g TS)	84.8	36.2
COD_{diss} (% COD_{tot})	12.5	34.9
NH_4-N (g N/L)	0.281	0.289
PO_4^{3-} (g P/L)	0.1	0.1

Table D4: Characteristics of the effluent.

The heavy metal (Cu, Cd, Pb) concentrations in the effluent were analysed by Atomic Absorption Spectrophotometry. As expected from a clean substrate, the measured concentrations were far below concentrations that inhibit the anaerobic processes.

System performance

The overall performance of the evaluated digesters was good. The study showed that the recommended feeding rate by ARTI-TZ of 8 kg (wet weight) organic waste for the Azania plants can be doubled without impairing the digester activity. However, this amount of food waste is not available at Azania and therefore new sources of food waste, e.g. from other schools or restaurants, would have to be considered to increase the performance of the plants and significantly reduce the charcoal consumption.

Costs and benefits

The initial cost for the complete system (three biogas plants, cement platform, three biogas stoves and training) at Azania Secondary School amounted to 8 850 000 TZS (6 404 US$ as of March 2010). The installation was entirely funded by Costech (Tanzania Commission of Science and Technology). As the students are responsible for feeding and operating the biogas plant, no operational costs are incurred and maintenance costs are negligible.

Various tests show that around 3.2 kg of charcoal can be substituted by 1 m^3 of biogas (depending on the meal and the way it is prepared). The monitoring programme revealed that 35 kg/week of charcoal can be saved if the biogas plants are fed with 8 kg each (thus 24 kg in total). This results in a reduced charcoal consumption of 1.83 t per year which is equivalent to 28 bags charcoal of 65 kg each. As one bag costs around 30 000 TZS, the yearly savings amount to 840 000 TZS. Hence, with an initial cost of 8 850 000 TZS the payback period is about 10.5 years. As this biogas system would be capable of processing double the currently recommended feeding rate, this payback period could be halved.

Practical experience and lessons learned

For future projects, emphasis needs to be placed on estimating daily available food waste amounts, design of the gas burner and gas stove, and intensive training of the people working with the biogas plants. This would help in utilising the biogas plant to its full capacity. Although switching from using charcoal to using only biogas seems an insurmountable challenge, it is a feasible option for partial substitution. This will foster improved organic waste management and reduce consumption of an unsustainable fossil fuel.

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E. Biogas Sanitation Systems in Nepalese Prisons

Project background and rationale

The armed conflict between Maoist armed opposition and government forces (1996–2006) led to an increased number of detainees in Nepalese prisons. Overcrowded jails and old infrastructure led to poor water, sanitation and environmental conditions. In 2004 the International Committee of the Red Cross (ICRC) decided to support the prison authorities in order to ensure that detainees had access to improved water supply and sanitation. In 2007, an agreement between ICRC and the local expert partner "Biogas Sector Partnership Nepal (BSP-N)" was signed to implement five biogas sanitation systems in three District Jails in Nepal. By May 2008, the construction of all systems was complete and the plants were commissioned. After a year of operation the functionality of these new systems was assessed by Eawag/Sandec and their impact and acceptance evaluated.

Feedstock

The feedstock of the biogas plants in the prisons is human faeces and some kitchen waste. The average daily amount of human waste per adult person in Nepal is estimated to be 0.4 kg and 1.5 L of urine (Karki et al., 2005). Average use of water for flushing, anal cleaning and cleaning of toilet area was observed to be between 2 and 4 L per person and day. Kitchen waste was only added to 3 out of 5 digesters. The amount of kitchen waste added varied considerably between 3 kg/day and 45 kg/day in the different digesters. Table E1 summarises inputs of the different digesters.

Parameter	#1 10 m³	#2 20 m³	#3 10 m³	#4 35 m³	#5 10 m³
Number of detainees (pers.)	65	135	115	155	106
Total faeces (kg/d)	26	54	46	62	42
Total flush water (L/d)	195	405	345	465	318
Total urine (L/d)	97.5	202.5	172.5	232.5	159
Total kitchen waste feeding (kg/d) [+ L/d water for dilution]	3 [+ 3]	45 [+ 45]	0	3 [+ 3]	0
Total feed (L/d)	324.5	751.5	563.5	765.5	519
Active slurry volume (L)	7500	15300	7500	24900	7500

Table E1: Characteristics of influent.

Description of technology and design

The biogas plant design promoted under BSP-N is the modified GGC2047 model, the shape of which is based on a Chinese type fixed-dome digester (Figure E1). The five installed digesters have capacities of either 10 m³, 20 m³ or 35 m³. The number of prisoners varies from 100 in the smallest prison to 270 in the biggest prison, with all three prisons having a small separate female section.

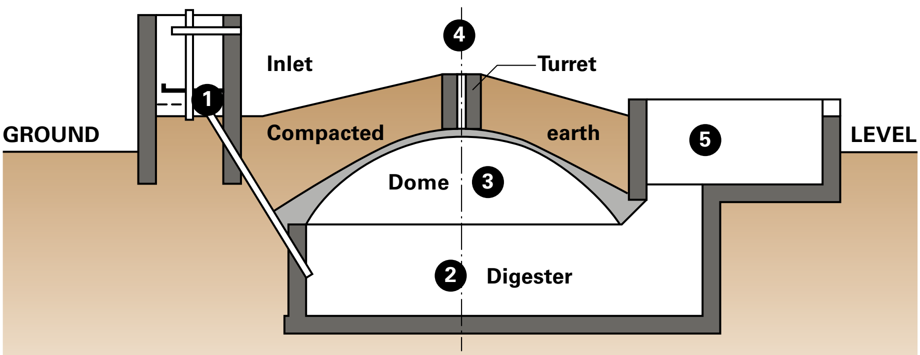

Figure E1: Blueprint of a 10 m³ biogas digester model GGC2047. 1) Inlet chamber with inlet pipe, 2) Digester, 3) Dome (gas storage), 4) Gas outlet, 5) Compensation/expansion chamber with overflow-point (BSP-N, 2008).

The toilets of the detainees as well as the prison kitchen with its biogas stoves are located within the prison walls, while the digester and effluent pits are situated outside the prison perimeter and are thus not accessible to the inmates (Picture E1). Feeding chambers for kitchen waste were either built inside or outside the internal prison perimeter. Usually one detainee is assigned responsibility for kitchen waste management and gets a monthly salary from the other inmates for this task.

The main operational parameters are shown in Table E2. It was not possible to calculate the organic loading rate as representative samples of feedstock for analyses of specific VS content could not be extracted.

Picture E1: Biogas sanitation system in Nepali prison with solid waste feeding chamber, gas outlet, underground dome and effluent pit outside the prison wall (photo: Sandec).

Parameter	**#1** 10 m^3	**#2** 20 m^3	**#3** 10 m^3	**#4** 35 m^3	**#5** 10 m^3
HRT (d)	23	20.5	13.5	32.5	14.5
T (°C)	26.4	25.6	29.8	28.8	30
pH	7.2	7.1	7.1	7.4	7.2

Table E2: Operational parameters. The approximation 1 kg substrate (wet weight) = 1 L is used for calculation of HRT.

Gas production

The average gas production in the digester using only human waste as feedstock was roughly 30 L/person/day. With additional feedstock of kitchen waste - in one prison all the kitchen waste was added - the gas production increased considerably up to 60 L/person/day. In each digester the gas production varied according to input quality and quantity. Specific gas production could not be calculated as the specific VS content in the influent could not be estimated (Table E3).

Parameter	**#1** 10 m^3	**#2** 20 m^3	**#3** 10 m^3	**#4** 35 m^3	**#5** 10 m^3
GPR (m^3/m^3 digester d)	0.282	0.602	0.441	0.172	0.459
Average CH_4 content (%)	67	57	76	78	72
Average CO_2 content (%)	25	34	20	17	27

Table E3: Gas production and composition.

Use of biogas

The study showed that the use of biogas is suitable for cases where both strictly regulated cooking for large groups (with up to 15 persons) and unregulated individual use by numerous detainees is practiced. It is recommended that all the gas produced per day is consumed in order to reduce purchasing of conventional cooking fuel and to avoid losses given the limited gas storage capacity of the digester dome.

Quality and use of the effluent

The TS, VS and COD content of the effluent serves as a good indication of treatment efficiency. The lower the COD concentration, the more efficient the performance of the biogas facility. The effluent was observed to be a liquid slurry with a low TS content. The share of organic matter is rather low with VS between 24 % and 44 % and a COD content of around 0.5 g/L, which indicates a satisfactory efficiency of the system (Table E4).

Parameter	#1 10 m^3	#2 20 m^3	#3 10 m^3	#4 35 m^3	#5 10 m^3
TS (%)	0.21	0.37	0.15	0.17	0.23
VS (% of TS)	39	44	32	24	39
COD (g O_2/L)	0.6	2.04	0.57	0.58	0.65
N_{tot} (g N/L)	0.69	1.03	0.71	0.7	0.65
NH_4-N (g N/L)	0.47	0.63	0.36	0.46	0.44
P_{tot} (g P/L)	0.06	0.11	0.04	0.05	0.05

Table E4: Characteristics of effluent.

Analyses of effluent in the storage pits revealed acceptable E. Coli concentrations allowing restricted irrigation according to the WHO guidelines on the safe use of wastewater (WHO, 2006). In some cases however, helminth eggs, another indicator organism, were not completely eliminated by the anaerobic digestion and sedimentation processes.

The effluent was not used as fertiliser in any of the three cases due to local circumstances and psychological barriers. These include:

- The slurry exit and storage is located outside the prison walls where detainees have no access. The area around the biogas facilities, although used for agriculture, is also part of the external prison perimeter and thus not accessible for the detainees.

- The security forces and wardens who cultivate crops (mostly maize) in the external prison perimeter reject the use of treated faecal matter in general, and in particular because it represents human waste from the prisoners.
- The security forces and wardens currently do not use any (organic or chemical) fertiliser for their crops as they do not see the necessity.

System performance

This type of system with underground fixed-dome digesters, compensation chambers and overflow point is well established and appropriate for the Nepalese context. Careful attention should be paid to compliance with the standard design, e.g. sufficient slope on the inlet pipe, a gradient for effluent drain-off and backfilling of soil. The rather elaborate mixing chamber for cow-dung inoculation is considered unnecessary and the assumptions used for design of the digester size need to be reconsidered (flush water, gas production from kitchen waste).

Costs

Economic benefits are directly influenced by the amount of biogas produced, as this replaces other cooking fuel, as well as the savings of money previously spent for emptying the septic tank. These figures differ for each jail. In the jail where kitchen waste is added to the digesters, 41 % of the money previously spent for conventional cooking fuels can be saved due to biogas substitution. In the other jails, savings of 17 % and 22 % have been reported since the installation of the biogas system.

The approximate payback period for each jail is listed in Table E5. The calculation regarding savings on cooking fuel costs is based on the average number of detainees between April and June 2009.

Parameter	**#1+2** (2 Digesters)	**#3+4** (2 Digesters)	**#5** (1 Digester)
Savings of cooking fuel (NR/prison/year)	29 400 (412 US$)	84 000 (1 176 US$)	41 100 (575 US$)
Savings of septic tank emptying (NR/year)	46 000 (644 US$)	22 000 (308 U$)	2 200 (31 US$)
Cost of biogas system (NR)	511 000 (7 154 US$)	577 000 (8 078 US$)	160 000 (2 240 US$)
Approximate payback period (year)	**1.5**	**5.4**	**3.7**

Table E5: Approximate payback period (costs in Nepali Rupees, 100 NR = 1.4 US$ as of March 2007).

Social aspects

In general, the biogas systems are perceived favourably by the vast majority of detainees who reported a general improvement of living conditions. Of the interviewed inmates 59 % reported the advantage of reduced smoke in the kitchen (and thus less respiratory problems) and 49 % mentioned improved hygienic conditions.
In one jail quick acceptance of biogas was reported, while in the two other jails detainees expressed initial scepticism towards a system which transforms human faeces into cooking fuel. These detainees admitted that they initially feared transmissions of diseases through the biogas and a decline in the taste of food. However, after noticing that no such negative changes were mentioned by others, they cautiously tried out biogas-cooked food themselves. Experiencing no negative effects after consuming "biogas-food" and the prospect of saving a decent share of the daily allowances thus led to a change of perception.

Practical experience and lessons learned

The evaluation concluded that biogas plants are an appropriate solution for the combined treatment of blackwater and kitchen waste in prisons as well as in similar institutional facilities in developing countries. However, the best promotion of a technology is to ensure proper functioning and the respective acceptance by its users. For biogas digesters at institutions, issues of strong ownership and responsibilities for maintenance work are crucial aspects which need special attention. If not properly operated and maintained, adverse effects such as methane emissions (greenhouse gas) or health risks of leaking gas pipes in the kitchen can clearly exceed the benefits.

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F. Decentralised Co-Digestion of Faeces and Organic Solid Waste in Lesotho

Project background and rationale

In 2002, the Maseru based NGO "Technologies for Economic Development" (TED) was established to implement biogas sanitation systems. With its specific technical design - and incorporating wastewater into the feeding material - a solution for one of the most pressing problems for households, i.e. lack of water and yearly emptying of septic tanks, was found. Up to 2010, TED, with the support of BORDA[1] had built more than 140 biogas systems of varying sizes. The TED biogas systems combined with DEWATS (Decentralised Wastewater Treatment System) elements proved to be suitable for the treatment of wastewater and worked well on both a household and settlement level. Today, biogas sanitation in Lesotho is provided as a technological package where wastewater and other organic matter are treated biologically, producing gas for cooking and digestate as soil conditioner.

TED follows a strictly demand driven approach. Action is only taken if they are approached by customers thus ensuring the economic viability of the operation.

In the framework of a study conducted in 2009 by Eawag/Sandec, 8 biogas systems were selected in order to monitor their performance.

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[1] Bremen Overseas Research and Development Association

Feedstock

The biogas plants monitored treat mainly black- and greywater from the toilet, bathroom, kitchen and laundry. Some households also feed kitchen waste and livestock waste (pig and chicken manure) to enhance gas production.

Description of technology and design

The TED biodigester design is the successor of the Tanzanian CAMARTEC model. It is a fixed-dome digester with a compensation chamber according to the so-called Chinese principle. The TED design provides a template for digester volumes ranging from 8 m^3 to more than 100 m^3. The construction procedure stays the same for all sizes.

The currently installed TED-Borda system consists of three parts (Figure F1):

1. **Digester:** Feedstock material (black water, kitchen waste etc.) enters the digester through the inlet. Inside the digester, the organic part of the material is slowly decomposed by bacteria. Biogas is generated as a product of the decomposition process. The biogas is stored within the upper part of the dome until it is released through the gas outlet. At a certain gas pressure (around 25 mbar) the biogas is released automatically through the digester outlet.
2. **Anaerobic Baffled Reactor (ABR):** The effluent coming out of the digester outlet enters an ABR. The reactor consists of a series of chambers, through which the effluent flows, passing though some sludge (containing bacteria) which has settled at the bottom of each chamber.
3. **Planted Gravel Filter (PGF):** The PGF is used as post-treatment of the effluent from the ABR. The main treatment processes within the PGF are biological conversion, physical filtration and chemical adsorption. These mechanisms of organic removal can be either aerobic and/or anoxic. The PGF is a horizontal flow planted filter consisting of graded gravel. At the end of the PGF there is an outlet tank to collect the treated effluent.

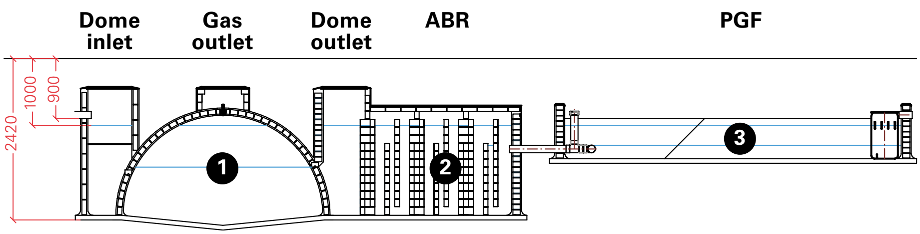

Figure F1: Scheme of DEWATS-Biogas-System of TED-BORDA. The basic build-up consists of an anaerobic digester (1), an anaerobic baffled reactor (ABR, 2) and an planted gravel filter (PGF, 3).

Gas production and use

The data presented in Table F1 shows that the biogas plants fed with animal dung (No. 5, 6, 7 and 8) generate a higher volume of biogas than digesters fed mainly with black water. The biogas is used for cooking and boiling bath water. An ordinary one-flame stove consumes about 0.3 m^3 biogas per hour. Some digesters provide 100 % of the energy demand for cooking in summer and 20–40 % in winter.

Monitoring of gas production shows that with longer periods of gas storage (e.g. gas not used) a decrease in average daily gas production can be observed. This is most likely due to increasing gas losses with higher pressure, either because of leakages in the upper part of the digester or automatic pressure release.

	Site	Feedstock	Digester Size	Average Biogas Production
1	**Garden site**	Black water	6 m^3	62 L/d
2	**Me Palesa**	Black water, kitchen waste (2.1 kg/d + 8.4 L/d water), grass	8 m^3	108 L/d
3	**Childrens Home**	Black water	9 m^3	62 L/d
4	**Mr Monethi**	Black water	6 m^3	193 L/d
5	**Mrs Ntsihele**	Pig waste (14 kg/d), black water	18 m^3	> 1 000* L/d
6	**Me Lerato**	Chicken + pig waste, paper	9 m^3	~ 800* L/d
7	**Mazenod**	Black water, cow dung	6 m^3	~ 600* L/d
8	**Mrs Nthama**	Chicken waste, black water	9 m^3	~ 1 000* L/d

* Values are derived from interviews. They can only be seen as approximate values.

Table F1: Biogas production and consumption.

Quality and use of the effluent

Table F2 presents the COD concentration of the digester inflow and compares it to the COD concentration in the effluent from the biogas digester, ABR and PGF. Results show that when comparing COD removal, plants that are also fed with agricultural wastes do not achieve the same treatment performance as those fed only with household waste. Basically, these systems are overloaded and the target effluent COD concentration of 0.12 g/L cannot be met. The effluent from some systems is reused for irrigation in the garden.

	Site	Feedstock	Digester Inflow (g/L)	Digester Effluent (g/L)	ABR Effluent (g/L)	PGF Effluent (g/L)
1	**Garden site**	Black water	0.456	0.303	0.171	0.134
2	**Me Palesa**	Black water, kitchen waste (2.1 kg/d + 8.4 L/d water), grass	2.847	2.293	1.863	0.373
3	**Childrens Home**	Black water	n/a	1.350	0.869	0.357
4	**Mr Monethi**	Black water	n/a	0.472	0.366	0.267
5	**Mrs Ntsihele**	Pig waste (14 kg/d), black water	1.489	1.505	n/a	1.318
6	**Me Lerato**	Chicken + pig waste, paper	6.342	n/a	n/a	n/a
7	**Mazenod**	Black water, cow dung	n/a	0.687	0.631	0.546
8	**Mrs Nthama**	Chicken waste, black water	n/a	0.755	0.501	0.450

Table F2: COD of inflow compared to effluent from digester, ABR and PGF.

Costs

When evaluating the economic aspects of the biogas systems implemented by TED-BORDA, the cost of an alternative wastewater treatment option needs to be taken into consideration. In the case of Maseru, storage tanks are typically used as the alternative. However they need to be emptied regularly as storage tanks with a soak-away are either not allowed by authorities or do not function properly due to the soil conditions. Regular emptying of the storage tanks is expensive and commercial servicing utilities can barely meet the demand. This is why many private households, landlords of rental houses and institutions invest in a Biogas/DEWATS system provided by TED-BORDA.

Storage tanks that have to be emptied regularly (about twice a month) by the municipal Water And Sewerage Authority (WASA) costs about 250 Maluti (25 US$) per tank load. This amounts to about 500 Maluti service costs per month for a household, and 6000 Maluti per year. In comparison, a biogas plant only has to be emptied approximately every 5 years (based on accumulation rate of settled solids within the digester).

Investment costs of the biogas systems are higher than those of storage tanks, but the operational costs are far lower. In addition, produced biogas replaces bottled gas or other energy sources for cooking, thus providing further savings. Table F3 presents the economic aspects of the biogas system. The labour required for feeding and operating the plant has not been considered. The results show that four of the evaluated systems (digesters 5–8) have a positive yearly balance, i.e. the owners save money when replacing storage tanks with a TED system, as they spend less money on bottled gas for cooking.

	Site	Invest-ment Costs	Capital Costs Annuity (2%, 15 year)	Operation Costs	Savings Bottled Gas*	Result
	Storage tank	5000 M	390 M/year	6000 M/year	0	- 6390 M/year
1	**Garden site**	16000 M	1200 M/year	50 M/year	~ 140 M/year**	- 1110 M/year
2	**Me Palesa**	16000 M	1200 M/year	50 M/year	~ 250 M/year**	- 1000 M/year
4	**Mr Monethi**	16000 M	1200 M/year	50 M/year	~ 440 M/year**	- 860 M/year
5	**Mrs Ntsihele**	30000 M	2300 M/year	50 M/year	~ 2500 M/year	+ 150 M/year
6	**Me Lerato**	16000 M	1200 M/year	50 M/year	~ 1800 M/year	+ 550 M/year
7	**Mazenod**	16000 M	1200 M/year	50 M/year	~ 1300 M/year	+ 50 M/year
8	**Mrs Nthama**	16000 M	1200 M/year	50 M/year	~ 2300 M/year*	+ 1050 M/year

* Based on a bottled gas (19 kg) price of 250 Maluti.
** Biogas is not yet used (digester is not connected to the kitchen). Values represent potential savings.

Table F3: Economics of wastewater treatment systems on household level; 1 M = 0.1 US$.

Practical experience and lessons learned

Most of the biogas plants were installed to replace wastewater storage tanks. There are several advantages of these systems compared to the storage tanks including:

- The owner no longer requires regular emptying of a storage tank which saves money and associated problems (e.g. overflow due to delays in tank emptying).
- The biogas system provides biogas that replaces expensive bottled gas or other energy sources.
- The biogas system provides an effluent that can be used for irrigation.

The treatment performance of the analysed plants varied widely depending on feedstock amounts and composition. Although the overall performance can be considered as good, the main challenges were identified as:

- Most of the digesters seem to have gas leakages.
- The performance of most of the ABR's was not satisfactory due to the slow build-up of activated sludge in the bottom of the chambers, sometimes taking several months.

- Overflow of effluent. If the plant cannot cope with the high amount of feedstock or if rainwater enters the system, effluent can overflow. This results in complaints by the neighbours due to the mess and smell.

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G. Anaerobic Digestion of Municipal Solid Waste in Gobernador Crespo, Santa Fe Province, Argentina

Project background and rationale

Gobernador Crespo is located 150 km north of Santa Fe and 170 km south of Reconquista (Province Santa Fe) on National Route N°11, which connects Buenos Aires (Argentina) and Asuncion (Paraguay).

In 1998 the local government decided to carry out a Solid Waste Treatment Plant project under the technical supervision of FIQ-UNL (Facultad de Ingenieria Quimica, Universidad Nacional Litoral). This project was funded by the World Bank and developed by PROMUDI (Programa Municipal de Inversiones). An anaerobic digester with a volume of 150 m^3 was built to treat organic waste from the tannery, the municipal slaughterhouse and domestic waste of 5 500 inhabitants.

Feedstock

A statistical study was conducted by Gobernador Crespo Commune to evaluate the quantity and quality of solid waste generation. The results are presented in Table G1, indicating the theoretical amount of available organic waste for anaerobic digestion based on the mass of non-organics that were removed from the total waste.

Type of Waste	Total Waste (kg/d)	Non-organic Recyclables (kg/d)	Organic Waste (kg/d)
Domestic waste from Gobernador Crespo Commune	2 057	617	1 440
Domestic waste from La Penca Commune	143	43	100
Leaves, grass, etc.	1 107	-	1 107
Organic waste from the tannery	171	-	171
Waste from the municipal slaughterhouse	1 429	-	1 429
Total Waste	**4 907**	**660**	**4 247**

Table G1: Data of statistical waste study in Gobernador Crespo.

Description of technology and design

The following process is followed for organic waste segregation and treatment:

- Organic waste is collected in separate bags.
- The bags of organic waste are opened and emptied onto a conveyor belt which transports the domestic waste to a hammer mill hopper to reduce the particle size (Picture G1).
- The chopped organic waste is then raised up through a worm gear to the mixing tank where it is diluted with recirculated effluent of the AD plant.
- The anaerobic digester is a floating-drum type with a volume of 150 m^3 (5.75 m diameter, total height 6 m) and the gasholder has a volume of 70 m^3. Both anaerobic digester and gasholder drum are made of fibre glass reinforced polyester (Figure G1).
- The effluent and digestate from the anaerobic digester is discharged onto a drying bed and then later used on an agricultural field adjacent to the AD plant.

In 2008, the digester in Gobernador Crespo Commune was modernised (Picture G2). A water-based heater was integrated into the system to heat the digester in winter. Biogas is used in an automatic burner to heat the water. Components such as water heater, heat exchanger, control system and pumps are protected under a roof to prevent damage.

Picture G1: Sorting of municipal solid waste from Gobernador Crespo (photo: Eduardo S. Gropelli).

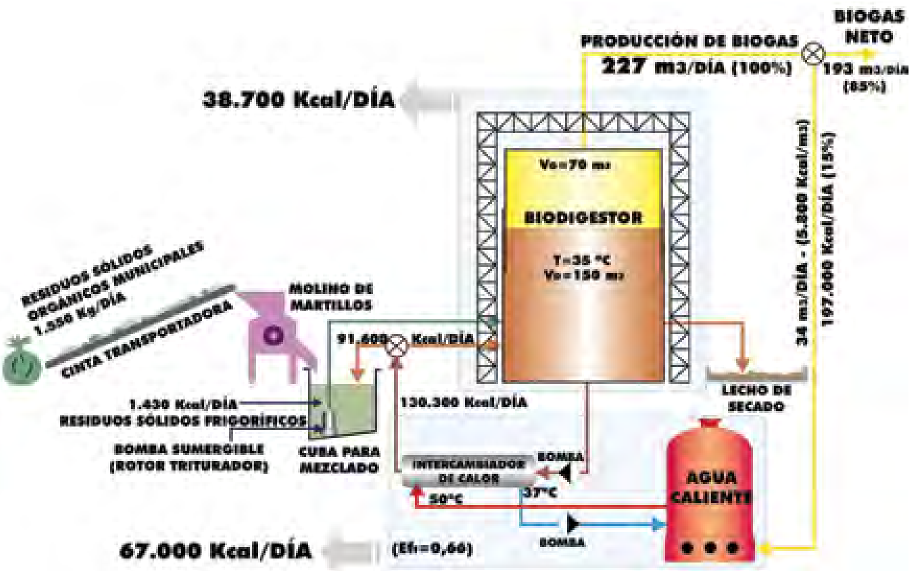

Figure G1: Scheme of waste treatment plant at Gobernador Crespo.

Picture G2: AD plant in Gobernator Crespo: a) before modernisation, b) water heater, c) automatic burner, d) after modernisation, e) protected components (photo: Eduardo S. Gropelli).

Input and operational parameters

A technical report completed in October 2009 indicated that only 12 tons of organic waste per month (550 kg/day) is fed to the digester instead of the 29 tons per week that was projected in 1999. Neither the tannery nor the municipal slaughterhouse is delivering waste to the plant. No information is available concerning TS, VS and OLR. The minimal retention time is 20 days and operational temperature is maintained at 35 °C.

Gas production

The average biogas production is 55 m^3/day. However, during winter time, 34 m^3 of this biogas is reused for heating the digester. Table G2 presents the energy balance of the AD system during winter and summer.

Parameter	Winter	Summer
Total biogas production (m^3/d)	55	55
Biogas used for digester heating to 35 °C (m^3/d)	34	0
Equivalent of biogas used for electric energy of 42.75 KWh (m^3/d)	12.15	12.15
Net biogas production (m^3/d)	8.85	42.85
Net energy produced as equivalent to LPG (Liquefied Petroleum Gas) (kg LPG/d)	**4.06**	**19.64**

Table G2: Energy balance in winter and summer of AD system in Gobernador Crespo.

Use of biogas

The biogas is used for heating purposes which includes heating of the digester, water and changing rooms.

Costs

The project was funded by the World Bank. Between 1996 and 1998, 117 895 US$ were invested in the Solid Waste Treatment Plant (according to Ing. Eduardo S. Groppelli). Later in 2007 and 2008 a further 10 000 US$ was invested to modernise the plant.

Practical experience and lessons learned

Due to lack of maintenance and communication problems with the municipality, the AD system in Gobernador Crespo has not been operated successfully. Efforts are ongoing in order to improve the performance and increase the weekly input into the digester.

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H. Anaerobic Digestion of Agricultural and Domestic Solid Waste in Emilia, Santa Fe Province, Argentina

Project background and rationale

Emilia is located in General López, Santa Fe Province, northeastern Argentina. In October 2002 a biogas plant was commissioned in the Municipality of Emilia, within the premises of the Private Technical School Monseñor Zazpe, where about 160 students and teachers live on weekdays. The facility processes all the organic waste of both the school and the city centre, which has a population of 800 inhabitants. The horizontal plug-flow digester is the first digester of this kind built in Argentina.

Feedstock

An analysis of waste available at the school and the village is presented in Table H1.

Type of Waste	**Raw Waste** (kg/d)	**Total Solids** (kg/d)	**Volatile Solids** (kg/d)
Agro-technical school			
- poultry manure	5.0	1.8 (36.0 % of raw waste)	1.6 (88.9 % of TS)
- pig manure	15.0	2.7 (18.0 % of raw waste)	2.2 (81.5 % of TS)
- canteen waste	6.0	1.1 (18.3 % of raw waste)	1.0 (90.9 % of TS)
Village			
- domestic organic waste	240.0	45.6 (19.0 % of raw waste)	41.0 (89.9 % of TS)
Total Waste	**266.0**	**51.2 (19.2 % of raw waste)**	**45.8 (89.5 % of TS)**

Table H1: Available organic waste for AD plant in Emilia.

Description of technology and design

The following process is followed for organic solid waste segregation and treatment:

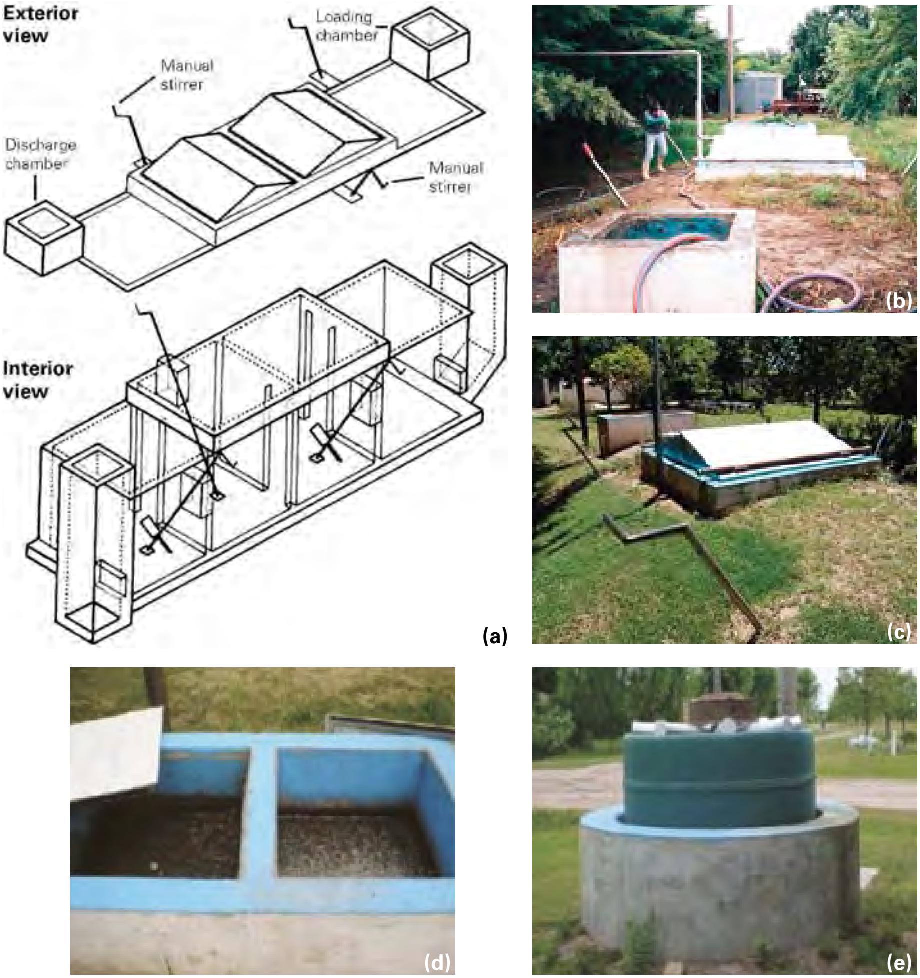
- Organic matter and other recyclables (i.e. paper, cardboard, glass, plastic, aluminium, etc.) are segregated at household level. The bags of organic waste are collected from door-to-door.
- Organic solid waste, without prior crushing, are gravity fed onto a loading chamber before entering the digester (volume 24.75 m^3).
- The digester is a horizontal plug-flow design with a square cross section of 2.3 x 2.05 meters and a length-to-width ratio of 5:1. The digester consists of a concrete slab at the bottom and concrete side walls (thickness 15 cm). The top part of the digester is constructed from concrete with a stainless steel section which can be removed for maintenance work.
- The generated biogas is transported through 150 m of underground polyethylene pipes to the kitchen of the school, where it is used for cooking.
- 2 m^3 gas holder is used to temporarily store the produced biogas.
- The digester is stirred using three hand-operated mixing devices made of stainless steel which are distributed throughout the length of the digester.
- The digested waste is removed at the exit of the digester using a submersible pump with a rotor shredder. This submersible pump can handle slurries and is also used to recycle 30 % of the digested suspension back into the digester.
- Retention time is 45 days.
- The digester is partially underground to maintain relatively constant temperature, 18 °C in winter and 24 °C in summer.

Input and operational parameters

The input characteristics and operational parameters of the AD in Emilia are presented in Table H2 and the gas production parameters are given in Table H3.

Parameter	Average Value
Daily feed (kg wet weight/d)	100
Water added (L/d)	450
TS (% of raw waste)	19.2
VS (% of TS)	89.5
OLR (kg VS/m^3 d)	0.69
HRT (d)	45
T (°C)	24 (winter: 18)

Table H2: Input characteristics and operational parameters of AD plant in Emilia. The approximation 1 kg substrate (wet weight) = 1 L is used for calculation of HRT.



Picture H1: a) Schematic of horizontal plug-flow digester at Emilia, b) and c) Overview of AD plant, d) Outlet of anaerobic digester, e) Gas holder (photo: Eduardo S. Groppelli).

Gas production

Parameter	Average Value
Daily gas production (m^3/d)	25
GPR (m^3/m^3 digester d)	1.01
SGP (m^3/kg VS)	1.46
Average CH_4 content (%)	n/a

Table H3: Gas production of AD plant in Emilia.

Use of biogas

The daily biogas production of 25 m^3 (equivalent to 15 kg of LPG) is used to make candies, jams and other foods to supply the school dining hall, and is also used to heat water.

Costs

The digester was built thanks to a contribution from the Rotary Club International and the work was carried out by the technical department of the School of Chemical Engineering of the Universidad Nacional del Litoral. Construction costs amounted to 35 000 Argentine pesos (8 066 US$ as of November 2011).

Practical experience and lessons learned

For successful implementation of AD systems, not only does the technology need to be adequate but people also need to understand and appreciate the benefits of the digester. They need to collaborate by separating organic and inorganic waste. Workshops and courses on the importance of digesters and how to segregate waste are required and these are conducted regularly in Emilia. This results in successful operation of this AD system.

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Anaerobic digestion (AD) reduces the amount of waste and generates products of value, such as biogas and nutrient-rich digestate. Contrary to the wide dissemination of digesters in rural areas where animal manure is used as feedstock and despite its apparent potential, AD still plays a negligible role as a treatment option for organic kitchen and market waste in cities of low-and middle-income countries.

This book compiles existing and recently generated knowledge on AD of urban biowaste at small and medium scale with special consideration given to the conditions prevailing in developing countries. Written for actors working in the waste and renewable energy sector, the book is divided into two parts: Part 1 focuses on practical information related to the AD supply chain (substrate-, process-, and product chain), and Part 2 presents selected case studies from around the world.