# The potential of flexible balloon digesters to improve livelihoods in Uganda. A case study of Tiribogo

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# Chapter 2: African biogas initiative

## 2.1 Biogas in Sub-Saharan Africa

Biogas technology is a renewable option in Africa that can be used to help ease energy and environmental problems. In SSA, interest in biogas technology has been further promoted by the efforts of various international organisations and foreign aid agencies. Thirty million Euros has been set aside by the Netherlands government to support the African Biogas Partnership Programme (ABPP), in Benin, Burkina Faso, Cameroon, Ethiopia, Kenya, Rwanda, Senegal, Tanzania and Uganda financing 70,000 digesters, knowledge management, fund management and technical assistance over a five year programme (2009 to 2013). SNV provides advisory services, with aim of improving basic services, production, income and employment for people in developing countries. The organization has activities in agriculture, renewable energy, water and sanitation, education, forestry, health, tourism and inclusive business. The organization is active in 36 countries in Africa, Asia, Europe, and Latin America [SNV 2010].

SNV is committed in improving the energy situation in developing countries. The organization's main focus in energy sector is the biogas digester programme, and SNV has also projects related to biofuels, improved cook stoves and micro-hydropower. The first biogas programme was implemented in Nepal in 1989 and since then the program has been implemented in Vietnam (2003), Bangladesh (2006), Cambodia (2006), Lao PDR (2007), Pakistan (2009), Indonesia (2009) and Bhutan (2011) in Asia, as well as Senegal, Burkina Faso, Ethiopia, Tanzania, Uganda and Kenya under Africa Biogas Partnership Programme (ABPP). ABPP was started in 2008 and aims to build 70,000 biogas digesters by 2013. By 2010, 360,000 households have been equipped with SNV biogas plant globally. SNV together with Asian Development Bank aims to build additional one million plants by 2015 in their "Energy for All Partnership" programme [SNV 2010].

SNV calls its method of promoting biogas "multi-stakeholder sector development" approach. The organization is active in policy level, providing promotion, materials, training for constructors and users, quality control and maintenance. The actual construction is made by local mason, trained by SNV. Ultimately, SNV's goal is that after some years of implementing the programme, the local biogas sector can implement the programme and construct plants without SNV's involvement. (SNV 2010)

Pandey et al. (2007) reported that the first biogas plant was built in Uganda by the Church Missionary Society in Mbarara district in the early 1950s; the emphasis in this installation was on treatment of sewage. The same source reports that in the 1960's, some missionaries built one demonstration plant in Kotido district. Boshoff (1969/70), a PhD student based at Makerere University, extensively documented biogas technology in the country and built a digester at the university farm at Kabanyolo. Since then, biogas technology has been promoted by both government and non-governmental organizations; the Uganda domestic biogas programme has been implemented since 2009 with a target to construct a total of 12,000 biogas digesters with support from the Netherlands Development Agency, SNV. This ambitious target is to be achieved by the end of 2014.

The Uganda Domestic Biogas Programme (UDBP) shall focus on the development of the biogas sector in Uganda. Sector development plans indicate that the Programme will work in close cooperation with all relevant stakeholders including Government, Non-Government and private sector. All levels in the sector will be included; micro, through meso and macro levels. The stakeholders will be sufficiently equipped to fulfill the necessary functions through capacity building and other means as identified by the Programme. The goal of the programme is to improve the livelihoods and quality of life of rural and periurban farmers in Uganda through utilising the market and non-market benefits of domestic biogas. The overall objective of the UDBP is to disseminate domestic biogas in rural and peri-urban areas with the ultimate of establishing a sustainable and commercially viable biogas sector in Uganda.

Specifically, the objectives of the programme are:

i. To develop a commercially viable market oriented biogas industry
ii. To further strengthen institutions for sustainable development of the biogas sector
iii. To work towards achieving installation and use of 12,000 quality biogas plants in a period 5 years5
iv. To ensure sustainability and continued operation of all biogas plants installed under the programme.
v. To maximize all benefits of biogas plants, especially related to gender and use of bio-slurry.
vi. To utilize carbon revenue resulting from the GHG emission reduction of biogas plants constructed under the programme to establish a financially-sustainable national domestic biogas sector.

In terms of programme design, these objectives will be implemented through use of multi-stakeholder approach. The private sector strategy will be applied to enable the creation of a biogas construction sector; this will involve using locally trained contractors and masons, supported by national vocational training institutions.

It has been identified that prior to this Programme, the major constraints that hindered dissemination of biogas were due to the high cost of biogas. In order to reduce the cost barrier, it is intended that micro-finance institutions will provide loans to the end users. The government will also offer investment incentives. End users will be guarded against construction errors by ensuring that the masons provide a one year guaranty on works done. Various stakeholders are integrated in the programme by providing services in which their core business lies. For example; agricultural, livestock and rural development NGOs will be involved in extension services while Government Ministries will participate in policy guidance and monitoring of activities. The programme is expected to create new jobs and expand on the existing business sector.

By the end of the five years, the Programme will have achieved the following:

i. Saving of conventional fuel sources (annually, $ 83 will be saved for households purchasing 60% of firewood for cooking and kerosene for lighting, $119.7 saved for households purchasing charcoal for cooking).
ii. Reduction of workload especially for women and children.( about 0.7 hours of time collecting firewood is saved per day and 20% of the saved time is used for economic activity translating to $2.06 of added earnings).
iii. Improvement of health and sanitation conditions benefiting women and children in particular. (Each Household will be able to save $14.2 per year on latrine access and $ 0.94 saved on indoor pollution infections and diarrheal diseases)
iv. Increase in agricultural production with proper utilization of slurry .
v. Employment generation.
vi. Reduction in greenhouse gas emission especially carbon dioxide ($CO_2$)and methane.
vii. Constructed 12,000 new biogas plants in central, western and eastern Uganda with over 95%6 of the constructed biogas plants remaining functional through proper operation and maintenance.
viii. 80% of the biogas households will have facilities that enable proper bio-slurry use.
ix. 10% of the biogas plants will have introduced a second inlet pipe to allow future toilet connection to the plant.

By end of 2012; 25,015 small-scale digesters had been installed in nine SSA countries. In Uganda, 3,500 digesters have been installed since 2009 (figure 1), utilising both animal dung and human excreta.

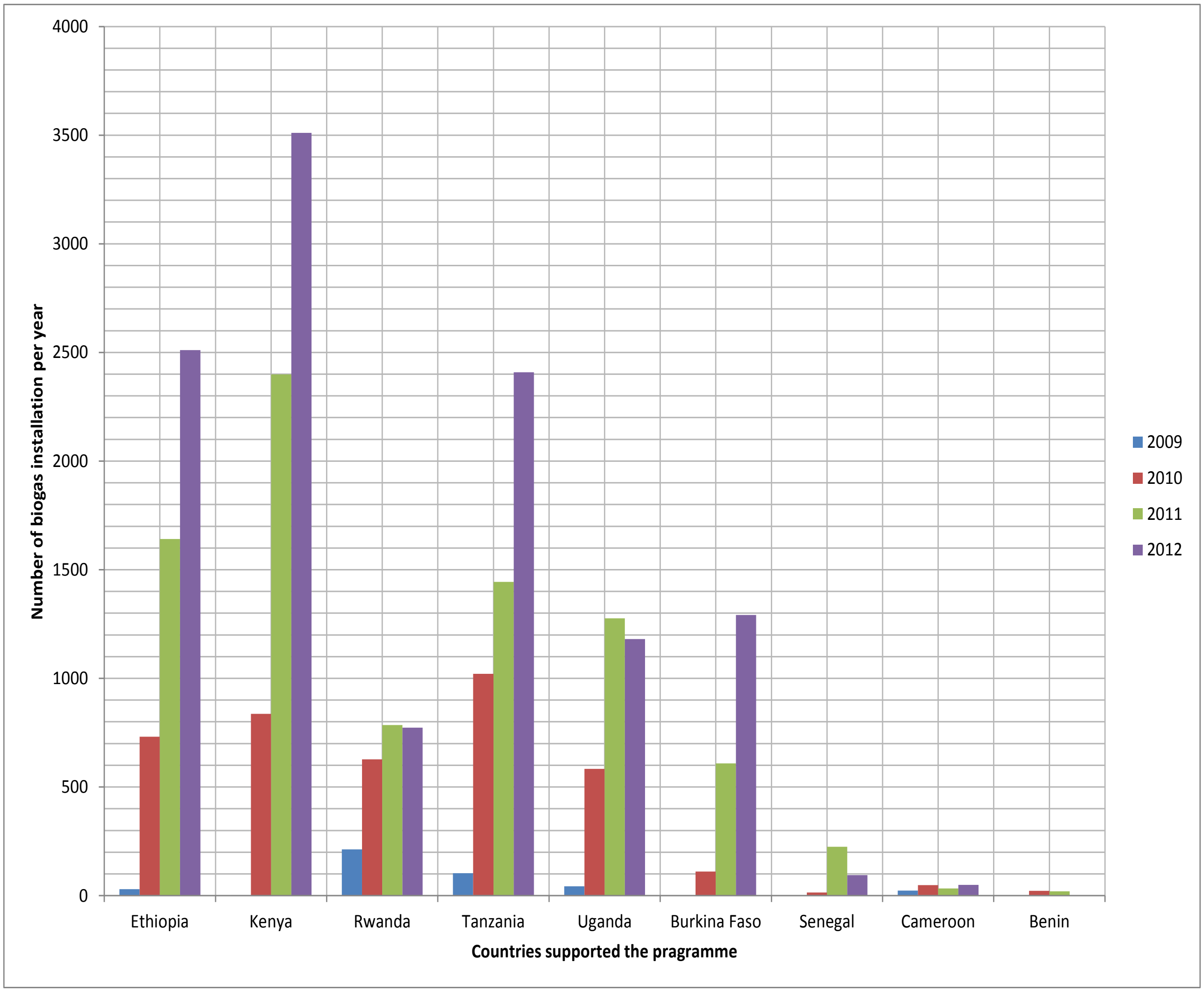


Figure 1: Total biogas installation per country (based on the figure by Heegde Felix, 2012)

## 2.2 The biogas production process

Anaerobic digestion (AD) involves the biochemical decomposition of complex organic materials in the absence of oxygen by various micro-organisms with the release of an energy rich gas (biogas) and the production of an effluent that is rich in nutrients (bioslurry/digestate). Digesters or reactors are physical structures that facilitate AD by providing an anaerobic environment for the organisms responsible for digestion.

### *2.2.1 Anaerobic digestion*

There are typically four main stages in AD; hydrolysis, acidogenesis, acetogenesis and methanogenesis (see figure 2).

1. Hydrolysis: This stage involves the extracellular enzymes, which transform molecular mass of organic lipids and polymers into simple compounds such as monosaccharides, fatty and amino acids. This phase requires a low pH.
2. Acidogenesis: Volatile fatty acids are produced after the initial hydrolysis stage. Fermentative bacteria degrade the simple compounds of sugars and amino acids to produce volatile fatty acids, acetate, hydrogen and $CO_2$. Ammonia is also produced in the process. Acidogenic bacteria prefer a pH range of 5.5 - 6.5 [Brummeler & Koster, 1989].
3. Acetogenesis: Here, the long fatty acid chain and volatile fatty acids are broken down to produce acetate, $CO_2$ and hydrogen. Acetogenesis bacteria prefer a pH range of 7.8 – 8.2 [Brummeler & Koster, 1989].
4. Methanogenesis: This is the last step in AD processes. Here, methanogenic bacteria convert hydrogen and acetic acid to $CH_4$ and $CO_2$.

The above AD process are shown in figure 2.

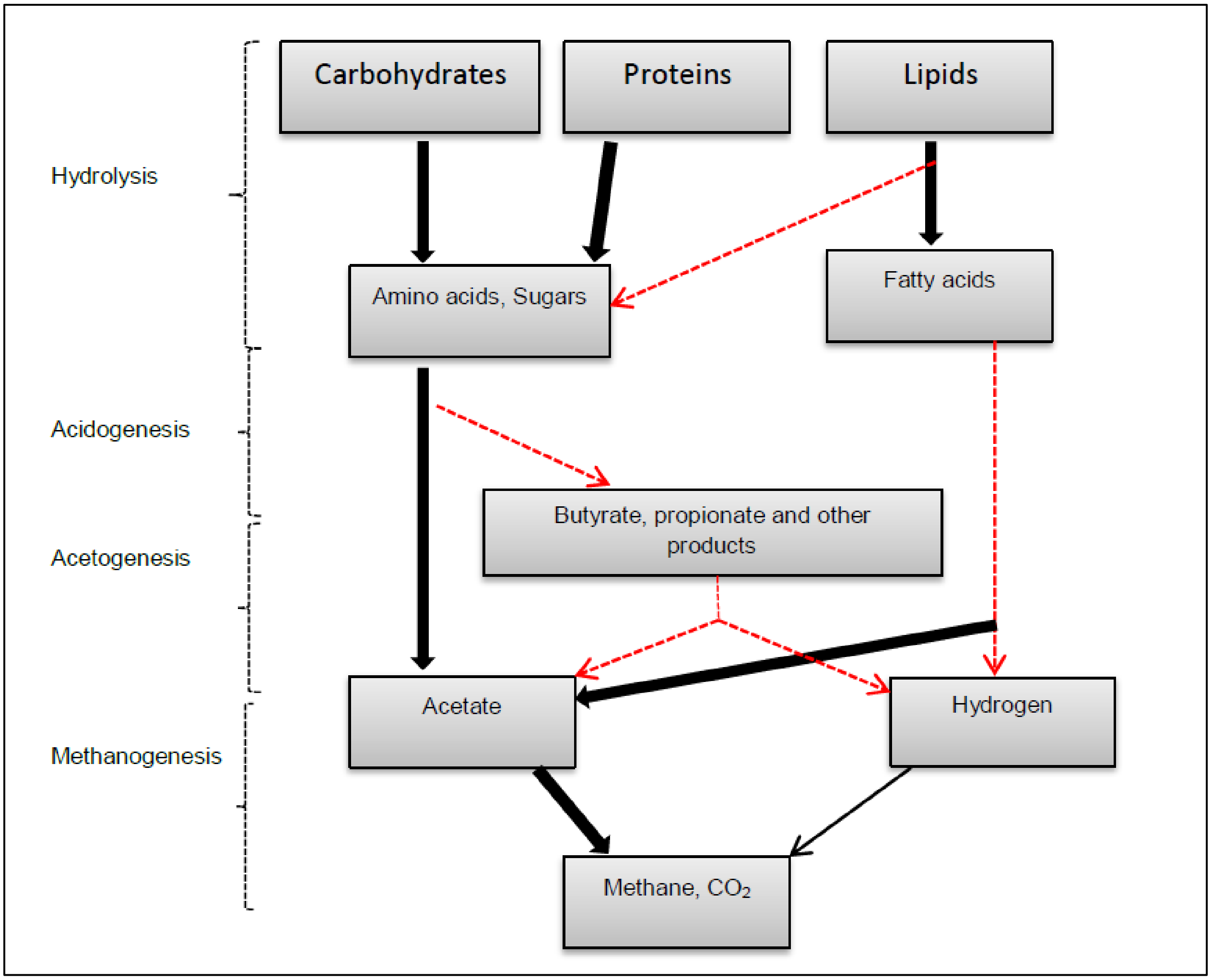


Figure 2: Anaerobic digestions stages [Mata-Alvarez, 2003].

Each stage is carried out by a different subset of micro-organisms operating in their own niche conditions. The pH affects the functionality of the micro-organisms; if the pH falls too low, the methanogens cannot convert the acids into $CH_4$ [Bernal et al., 2009]. During biogas production, microbial populations inside a biogas digester should be balanced. Mata-Alvarez (2003) observed that an overload with an excess of organic matter caused an abrupt change in temperature, accumulation of toxic substances, pH change, and a consequent impact on the rate of biogas production. Composition of waste is also important; too much nitrogen results in excess ammonium production and inhibits the process; too much carbon results in rapid hydrolysis and a fall in pH that also inhibits the process. The optimum C:N ratio of the feedstock is between 20 and 30 [Bernal et al., 2009].

In general, the higher the temperature, the higher the rate at which AD occurs, but this relationship is non-linear. Small-scale biogas digesters in SSA usually operate at ambient temperatures or soil temperatures if the digester is installed below the surface of the soil.

### *2.2.2 What is biogas?*

Biogas is composed of a mixture of colourless gases including $CH_4$ and $CO_2$. Other components of biogas are shown in Table 1.

**Table 1: Composition of Biogas**

| **Component** | **Percentage** |
|---|---|
| Methane | 50-70 |
| Carbon dioxide | 30-40 |
| Hydrogen sulphide | Trace |
| Water vapour | 2 |

Source: Karki et al., 2005

### *2.2.3 Factors affecting biogas production*

*Temperature*

The physical environment provides the setting for the chemical reactions. Maintaining a constant temperature at the optimum range for the bacteria is critical for maximizing gas production. Anaerobic bacteria can endure temperatures alternating 0 to 57°C, but they flourish best at mesophilic temperatures around 36.7°C (the range for mesophilic bacteria is 30-37°C) or thermophilic temperatures around 54.4°C (the range for thermophilic bacteria is 50-60°C). However, digesters running in the mesophilic range are less sensitive to change in the operating routine than digesters operating in the thermophilic range, and so the mesophilic process can be more robust. Table 2 [Cheng, 2010] shows the temperature ranges, the average length of time liquids and soluble compounds remain in the digester (operating hydraulic retention time, HRT), growth and digestion rates, and tolerance to toxicity for the three anaerobic processes. Increasing HRT allows more contact time between substrate and bacteria, but requires a slower feed-rate or larger digester volume.

**Table 2: Comparison of AD digester type**

| **Digester type** | **Operating Temperature (°C)** | **Operating HRT (days)** | **Microbial Growth and Digestion Rates** | **Tolerance to Toxicity** |
|---|---|---|---|---|
| Psychrophilic | 10 – 25 | > 50 | Low | High |
| Mesophilic | 30 – 37 | 25 – 30 | Medium | Medium |
| Thermophilic | 50 – 60 | 10 – 15 | High | Low |

*Carbon to nitrogen ratio*

A C:N ratio, ranging from 20 to 30, is considered to be optimum for AD. If the C:N ratio is excessive, then, methanogens will rapidly consume the nitrogen in order to fulfill their protein requirements, and decomposition of the left over carbon content of the material will be inhibited by lack of nitrogen. This results in a low gas production. In spite of this, a low C:N ratio results in concentration of ammonium, which results in an increased pH, also inhibiting gas production. Optimum C:N ratios for the feedstock can be achieved by mixing feedstocks of high and low C:N ratios.

*Solid content*

The total solid concentration (TS) in the feedstock is crucial to ensure easy mixing and handling; 8-10% total solids (TS) or 20 to 100 g $dm^{-3}$ is the optimum range for biogas production [Bui Xuan An and Preston, 1999].

*Hydraulic retention time*

The hydraulic retention time (HRT) is the average period a given quantity of the feedstock takes to move from the inlet to the outlet pipes of a biogas digester. Hydraulic retention time estimated by dividing the digester capacity by the amount of feedstock fed into the digester per day. In general, the rate of digestion has a direct relationship on the retention time. Also, if the temperature inside the digester is raised, then the HRT is short (Table 2).

*Feedstock characteristics*

Table 3 shows the relationship between TS, volatile solids (VS) and biogas yield of different types of feedstock. The Food and Agriculture Organization of the United Nations (FAO) reported that biodegradable organic material can be used as inputs for processing inside the AD system. Most types of biomass can be used as substrates for biogas production as long as they contain the main components (carbohydrates, proteins, fats, cellulose or hemicelluloses) [Mata-Alvarez, 2003].

However, for economic and technical reasons, some materials are more favoured as inputs than others. Although existing digesters commonly use animal waste for gas production, plant materials also serve as a viable input feedstock. Since different organic materials have different biochemical characteristics, their potential for gas production varies. Therefore, substrate materials can be mixed to achieve the basic requirements for gas production and normal growth of methanogens. One of the biggest challenges arising from this process is to accurately predict the amount of $CH_4$ produced based on the feedstock used. This is because the nature and composition of substrate material dictates the microbial regime present, and no single set of parameters is valid for all situations [Bentley, 2010].

**Table 3: The maximum gas yield according to the total solid and volatile solid content of different organic waste**

| Substrate | TS [%] | VS [%] | Biogas yield [$m^3$/kg VS] | Source |
|---|---|---|---|---|
| Fresh cattle excreta | 25 - 30 | 80 | 0.6 - 0.8 | Deublein et al., 2008 |
| Cattle liquid manure | 6 -11 | 68 - 85 | 0.35 - 0.55 | Schilling & Tijmensen, 2004. |
| Kitchen waste | 9 - 37 | 50 - 70 | 0.2 - 0.5 | Eder & Schulz, 2006. |
| Market waste | 28 - 45 | 50 - 80 | 0.45 | Eder & Schulz, 2006. |
| Vegetable waste | 5 - 20 | 79 - 90 | 0.2 - 0.3 | Deublein et al., 2008 /Gunaseelan, 2004 |
| Banana skins | 8 - 20 | 86 - 94 | 0.2 | Gunaseelan, 2004 |
| Fruit waste | 25 - 45 | 90 - 95 | 0.4 - 0.7 | Deublein et al., 2008 |

Different feedstocks have different digestion properties, and result in biogas of different compositions and quality. Organic waste containing proteins, carbohydrates and fats, decompose easily, whereas organic wastes containing a high proportion of lignin, as found in wood products, are not easily broken down by AD [Riuji, 2009]. Choosing a stable mix of feedstock with superior energy content that is easily available to the bacteria, such as simple sugars and fats, maximises biogas production. By contrast, feeding the digester highly variable substrates with nutrients locked away in compounds that bacteria cannot easily digest, such as lignin and cellulose, leads to poor biogas yields. One of the most important factors to the successful implementation of a biogas digester is the availability of the feedstock.

The amount of biogas that could theoretically be produced from manure depends on the type or breed of livestock and the livestock management system. Sufficient quantities of feedstock, especially animal manures, are needed to produce biogas. Brown (2006) suggested that 1-2 cows or 5-8 pigs produce sufficient feedstock to provide biogas for a typical household. Smaller particles increase the productivity of the digester due to the increased surface area for increased biological activity [Igoni et al, 2008].

Typical household waste in Uganda is mainly composed of kitchen waste, food leftovers and vegetable and fruit peel and skins. A typical mix would include banana skins, stiff maize porridge (posho), rice and vegetables (often beans and spinach), fried potatoes and pieces of meat or fish with sauce. Households in Tiribogo keep cows and pigs and the remains of household food are usually fed to the animals. Manure from the cows or pigs can then be used for biogas production after mixing it with water.

*Pre-treatment of biodegradable feedstock*

Pre-treatment of the food waste can be achieved by using a manual meat mincing machine (figure 3) which has the capacity to reduce the food waste into particles of less than 1cm diameter (figure 4 and 5); this increases the surface area for the action of hydrolytic bacteria. A mortar and pestle can also be used instead of the meat mincer especially for rural households with limited access to mincing machines.

Figure 3: Mincing machine

Figure 4: Macerated food waste

Figure 5: Mixing manure

*Water availability*

Water availability for biogas production has been discussed by Orskov et al. (2013). Rosen and Vincent (1999) stated that water is collected and used for; cooking, showering, washing hands, laundry and utensils by many households in SSA. The quantity of water collected and used by each household is dependent on how accessible water sources are in the village. Water Aid [2012] proposed that the average person in SSA uses 10 $dm^3$ $day^{-1}$ for drinking, washing and cooking. Moisture is essential for bacterial activity; they are able to tolerate conditions ranging from small amounts of moisture to dilute solutions of nutrients. This means that very wet feedstock can be used without loss of energy consumed. Much of this water can be recycled into the biogas digester, so reducing additional labour for water collection. The amount of water required to run a biogas digester depends on the type and amount of feedstock. For optimal anaerobic fermentation, the dry matter content must be between 2 and 5% [Preston, 2011]. This means that for each 10 kg of dry matter, there is a need for about 200 $dm^3$ of water. Pandey et al. [2007] expressed this as approximately equal volumes of water and fresh dung being fed into the digester daily.

*Concentration of microorganisms*

Hydrolytic and acid forming bacteria have a short residence time compared to methanogenic microorganisms, whose residence time is between 10-15 days in the digester. These bacteria have a slow growth rate. Therefore, a new biogas digester requires about 3 months allowing time for the time for households to collect manure and for methanogenic bacteria to grow, [Deublein et al., 2008].

*Specific surface material and disintegration*

Feedstock size reduction increases the surface area for biochemical reaction and it increases the reaction rate. However, it does not influence biogas yield. Disintegration is the destruction of cells structure and the cell walls. Disintegration increases the degree of decomposition, and so yield of biogas can be increased [Deublein et al., 2008].

### 2.3 Digester types

Small-scale anaerobic digesters are usually operated as semi-continuous systems. A biogas digester is a sealed tank where the AD takes place. The digester has a feeding point, a gas storage chamber and effluent exit unit. A fixed amount of organic material is mixed with the appropriate amount of water (or urine) and fed into the digester once a day. The biogas generated is used for cooking meals throughout the day. A quantity of semi-solid slurry is displaced through the exit pipe into a slurry holding tank. The slurry is often applied directly to fields, but can also be composted. The three designs of digesters currently available are the fixed dome, floating drum and the flexible balloon digester.

### *2.3.1 Fixed dome digester*

The fixed dome design is currently being promoted in many countries in SSA.  It is a below ground digester constructed of brick and cement.  The digester is built on a circular concrete base using clay bricks (figure 6). The sides curve inwards to form a dome (figure 7) where the biogas collects and is stored. A neck is built onto the dome which is sealed by a cover to prevent gas leakage. This cover can be removed to conduct maintenance on the digester. A trained mason with proven experience is required to do the brick laying, plastering and fitting of the gas pipes. The digester is plastered inside with water-proof cement to make it gas-tight and to prevent leakage of the effluent (figure 8). The outside of the dome is well plastered and the excavation site back-filled with soil and then landscaped (figure 9).

These digesters are intended for large amounts of cow and other livestock waste, and the ground level input makes it easy to feed in this way. If cows are zero grazed, and therefore held in a pen all day, a concrete floor with drainage channels can be constructed to feed the waste directly into the digester.

Figure 6: Foundation of a fixed dome (by Green Heat Uganda - GHU)    Figure 7: Gas chamber under construction (by GHU)

Figure 8: Complete fixed dome (by GHU)    Figure 9: Digester in the ground (by GHU)

To start the AD, cow dung mixed with urine, rain water or water from a pond or borehole is fed into the digester through the mixing unit. The well mixed feedstock flows by gravity into the bottom of the digester. The lower part of the digester contains a layer of solids and a layer of liquid above the solids. As the anaerobic microbial processes take place, VS are consumed and $CH_4$ and $CO_2$ are produced. Biogas is stored within the digester, creating a gradual pressure buildup. As the pressure increases beyond the equilibrium point, the gas pressure will push digested slurry from the bottom of the digester up the expansion chamber. Some of the effluent in the expansion chamber moves back into the digester and increases gas production. The rest of the effluent flows into a slurry holding tank, where it can be stored safely and used either as compost or applied directly to crops.

Advantages of fixed-dome digesters are that the digesters have no moving parts, and the design lifespan is long (30 years) [Sasse et al., 1991], the maintenance costs are low, and it maintains stable temperatures within the digester. Disadvantages of fixed-dome digesters are that special water proof sealants are required, the costs of construction are relatively high, high technical skills are required for construction, and gas pressures fluctuate, which causes difficulties in the use of the gas [Sasse et al., 1991].

### *2.3.2 Floating drum*

A design of floating drum digester, developed in 1962, is the Khadi and Village Industries Commission (KVIC) digester. Even though the design is now over 50 years old, it is still one of the most widely accepted and used designs for household purposes in India. The design includes a movable inverted drum mounted on a movable guide frame. The drum floats either in a water jacket surrounding the digester or directly in the digesting slurry [Sasse et al., 1991].

Figure 10: Floating drum (by *Tumwesige*)

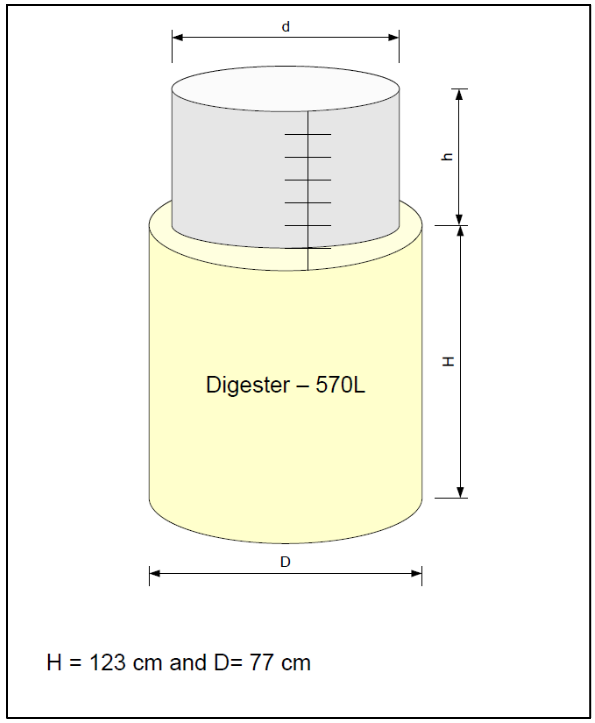


Figure 11: Proto type (by *Tumwesige*)

An inverted steel drum (figure 10 and 11) that acts as a storage tank is placed on the digester, which can move up and down, depending on the amount of gas accumulated at the top of the digester. The weight of this inverted drum applies the pressure needed for the gas flow through the pipeline for use [Singh & Sooch, 2004].

The Appropriate Rural Technology Institute (ARTI) developed a compact biogas system (figure 12), a simple design that uses locally available materials, and can be constructed in only a few hours by two or three people [http://www.ashden.org/winners/arti06].

Figure 12: ARTI floating drum (by *Tumwesige*)

The ARTI digester is designed to be fed with 2-10 kg of food waste per day. It utilizes two standard high density polyethylene (HDPE) water storage tanks and standard `plumber piping. The tops of the tanks are cut off, and the smaller one is inverted and placed inside the larger one. As the gas is formed it is stored in the inverted tank, which then “floats” on top of the water and feedstock slurry. In addition, digester tanks can be constructed of cement and brinks with a high density polyethylene tank as a gas holder.

Similarly to the fixed-dome digester, the slurry flows down the inlet pipe and enters the bottom of the digester. There is a layer of solids on the bottom and a layer of liquid effluent above that. The floating-drum design differs from the fixed dome in that it includes the drum made of either steel on a guide frame or a plastic tank.

Advantages of the floating drum digester are that the operator can easily see and better understand how the digester works because the dome rises and falls with higher and lower gas pressure. Floating-drum digesters are easy to operate [Sasse et al., 1991]. Gas tightness (the lack of gas leaks) is easier to maintain in the floating-drum design [Sasse et al., 1991]. Disadvantages of the floating drum digester are that the steel drum (if used) is relatively expensive and requires frequent maintenance. Also, the gas holder is extremely unstable and can tilt causing gas leakage. The design life of a floating-drum digester is only 5-10 years, compared to 30 years for a fixed dome digester. In addition, the drum can become jammed on the guide frame, requiring maintenance [Sasse et al., 1991]. According to Ocwieja (2010), floating drums are harder to obtain, leading to increased costs.

### *2.3.3 Flexible balloon digester*

Flexible balloon digesters consist of a narrow and long tank with, an average length to width ratio of 5:1. The inlet and outlet of the digester are located at opposite ends (figure 13) kept above ground, while the remaining parts of the digester is buried in the ground in an inclined position of 2-5% to facilitate gravity flow. As fresh substrate is added from the inlet, the digestate flows towards the outlet at the other end of the tank.

The gradient of the tube makes it possible to separate acidogenesis and methanogenesis longitudinally, thus producing a two-phase system. In order to avoid temperature fluctuations during the night and maintain the process temperature, a gable or shed roof is placed on top of the digester to cover it, which acts as an insulation both during day and night [Ferrer et al., 2011; Karagiannidis, 2012].

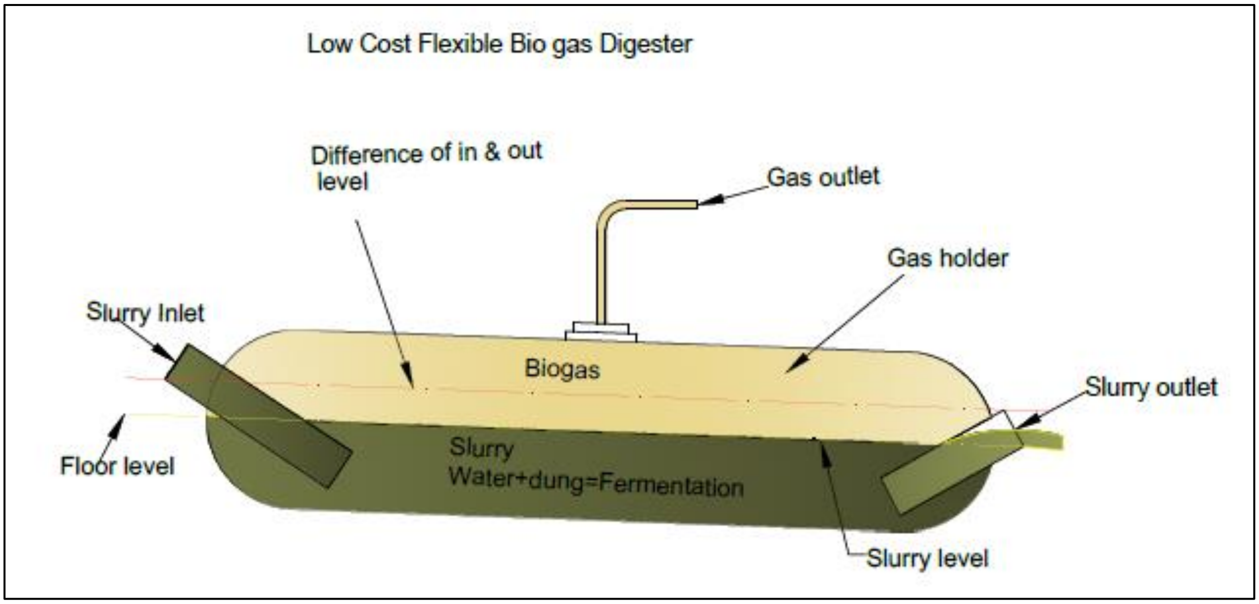


Figure 13: Sketchmatic of a flexible balloon

The advantages of these digesters include easy installation and easy handling.

## 2.4. Biogas stoves and lamps

### *2.4.1. Biogas stoves*

The $CH_4$ in biogas burns in oxygen to give $CO_2$, water and energy content. Understanding the combustion process provides a basis for the performance criteria and emission standards used to regulate manufacturing and marketing of quality biogas stoves. The chemical reaction occurring when biogas burns is shown below:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

From the above equation, one mole of $CH_4$ requires two moles of oxygen to give one mole of $CO_2$ and two moles of steam. According to the ideal gas law, this translates directly into volumes. Since there is 60% $CH_4$ in biogas and 21% oxygen in air:

$\frac{1}{0.6} = 1.667$ volume of biogas requires $\frac{2}{0.21} = 9.52$ volumes of air (i.e. 17.5% biogas in air);

Biogas burns over a narrow range of mixtures from approximately 9% to 17% of biogas in air. If the flame has too much fuel, then it will burn incompletely, producing CO, which is poisonous, and also producing more soot particles. The designs of appliances should aim at maximizing the conversion of $CH_4$ into $CO_2$ in order to minimize the release of unburned $CH_4$ and products of incomplete combustion. Stoves usually run with a small excess of air to avoid the danger of the flame becoming rich. If too much air is supplied, the flame cools off thus prolonging the working time and increasing the gas demand [Sasse et al., 1991].

Biogas stoves and other equipment are made in two parts: the burner itself (figure 14), which mixes gas and air and feeds it to the flame ports, where it burns; and the frame within which it sits, which uses the flame to heat cooking pots or to generate light or use the heat in some other way. The frame for a stove supports the burner on legs and holds cooking pots the right distance away from the flame for effective heating.

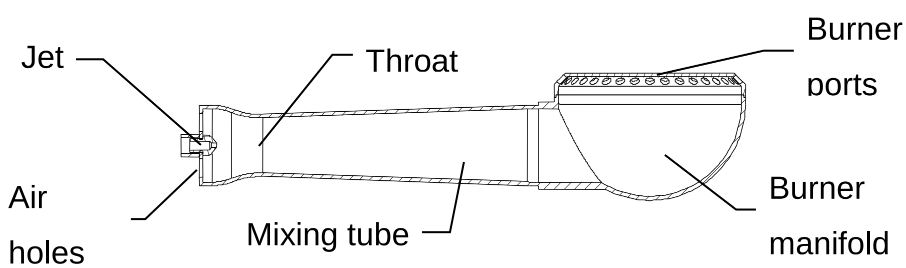


Figure 14: Parts of a biogas burner (Fulford, 1996)

The burner itself has several parts [Fulford, 1988]. The amount of gas that flows into the burner is controlled by the jet, a hole which is carefully sized and defines the power output of the burner. Most burners are partially aerated, which means that the gas is mixed with a proportion of primary air that is less than optimum for combustion. The air and biogas are mixed and fed to a manifold which feeds the flame ports, where it burns. Secondary air flows around the outside of the flame ports to complete the combustion process. The burner ports are drilled into a shaped cap, which can be removed for cleaning if food is spilled into the burner ports.

The optimum amount of air to allow a fuel gas to burn is called the stoichiometric mix and is 5.7:1 for biogas [Fulford, 1996]. The flow of gas from the jet, $Q$ ($kgm^2s^{-2}$), depends on the hole size and the gas pressure:

$$Q = 3.9 C_d A_0 \sqrt{\frac{p}{s}} \times 60,000 \qquad 1$$

where $C_d$ is the coefficient of discharge of the orifice (the dimensionless ratio of the actual discharge through the orifice to the theoretical discharge), $A_0$ is the area of the jet ($m^2$), $p$ is the gas pressure (mm water gauge), and $s$ is the specific gravity of the gas (dimensionless). Typical values of $C_d$ are between 0.7 and 0.9, depending on how well it is made, s is 0.94 for biogas. The power produced by a burner, $P$ (kW), is given by

$P = Q \times H / 60$, where $H$ is the enthalpy of combustion. The value of $H$ for biogas is 21.5 MJ $m^{-3}$, so $P$ can be expressed as

$$P = 3.9 H C_d A_0 \sqrt{\frac{p}{s}} \times 1,000 \text{ or } P = 3.9 W C_d A_0 \sqrt{p} \times 1,000, \qquad 2$$

where $W = H/\sqrt{s}$ is called the Wobbe number of the gas (= 22.2 MJ $m^{-3}$).

As the gas emerges from the jet, it accelerates, which, according to Bernoulli's theorem, reduces the pressure:

$$p + \tfrac{1}{2}\rho v^2 = \text{constant}, \qquad 3$$

where $p$ is the pressure (in Pa), $\rho$ is the gas density (kg $m^{-3}$) and $v$ is the gas velocity (in m $s^{-1}$). The reduced pressure entrains (draws in) air, which mixes with the gas in the mixing tube. The entrainment ratio $r$ defines the primary aeration (air introduced into a gas stream before it leaves the burner port) and is given by Priggs formula:

$$r = \sqrt{s\left(\sqrt{\frac{A_t}{A_0}} - 1\right)} \text{ or } r = \sqrt{s}\left(\frac{d_t}{d_0} - 1\right) \qquad 4$$

where $A_t$ is the area ($m^2$) and $d_t$ is the diameter of the throat at the narrowest part of the mixing tube (m). Typical values of $r$ are between 50% and 75%. The entrainment ratio is chosen to give an air flow that will provide a mix about twice that of stoichiometric or theoretical air requirement. The mixing tube can be made as a venturi tube, with a narrow throat with tapers leading in and out, or as a straight tube. The length of a straight mixing tube should be at least 10 × $d_t$ while a venturi tube can be 6 × $d_t$. The total flame port area ($A_p$) should be between 1.5 and 2.2 × $A_t$ for Priggs formula to work.

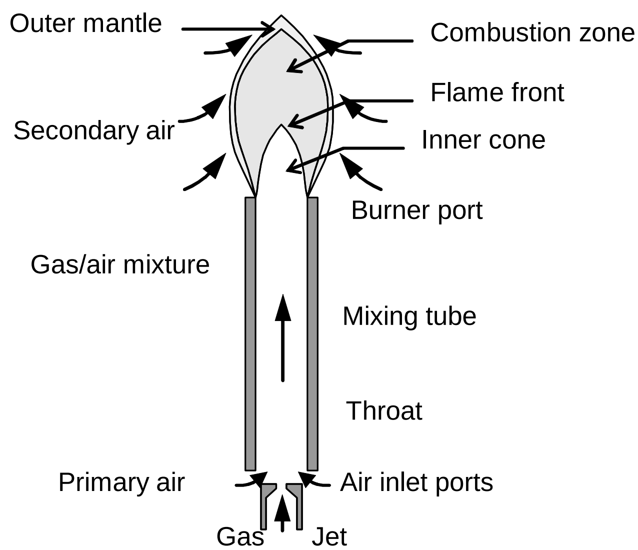


Figure 15: Parts of a gas flame (Fulford, 1996)

The flame height at the flame ports are affected by the primary aeration. A low value of r means the gas is seeking secondary air to burn (figure 15), so the flames are long and "lazy" and do not burn properly. Poor combustion generates poisonous CO and soot particles (which show as red flashes in the flame). A high value of *r* means that the gas can burn with the primary air, so the flame is much shorter. Full aeration is ($r = 5.5$) is inadvisable, as the flame can "flash back", i.e. jump through the flame ports, along the mixing tube and burn at the jet.

The flame ports need to be designed to allow easy access to secondary air flow. Various tricks have been used to stabilise a flame, such as ledges around the flame ports and using small secondary flames around the main one. The potential heat contained in biogas can be released when sufficient quantity of air burns with it.

Insufficient air would lead to loss of potential heat by incomplete combustion while an excess may give rise to loss of potential heat due to surplus heat production. Biogas has a low laminar flame speed ($v_{fl}$ = 0.25 m $s^{-1}$) [Fulford, 1996]. The flow in a flame port is turbulent, so the actual flame speed is higher. The velocity of the gas from the flame ports must be lower than the flame speed for the flame to be stable. Good mixing increases the flame speed, so improving the flame stability.

All gas burners follow the same principle; the force which drives the gas and air into the burner is the pressure of gas in the pipeline [Fulford, 1996]. A biogas stove can have a single or double burner with varying gas consumption rates ranging from 220 $dm^3$ $hr^{-1}$ to 450 $dm^3$ $hr^{-1}$ at standard temperature and pressure [Khandelwal, 2009; UNAPC, 2007]. This consumption rate results from the pressure provided by the biogas plant and the diameter of the inlet pipe. The jet at the inlet of the burner increases the gas speed, so producing a draft that sucks primary air into the pipe.

The stove must be designed to suit basic local requirements such as ease of cleaning, repair, good burning properties, safe to use, versatility, attractive appearance [UNAPC, 2007]. However, these requirements vary from location to location and are linked to local dietary and hence cooking requirements. The gas demand is higher in cultures with complicated cuisine and where whole grain maize or beans are part of the staple diet.

The overall efficiency of using biogas is 45% in stoves [George, 1997; Smith et al, 1993], 24% in engines and 3% in lamps [Sasse et al., 1991]. The efficiency of the given biogas stoves is not constant. It varies depending on the surrounding conditions; wind, temperature, pressure, shape, specific heat capacity and weight of vessel, burner size of stove and size of bottom face of cooking vessel, and the quality of the gas [Center for Energy Studies Institute of Engineering, 2004].

Liquified petroleum gas (LPG) stoves can be modified to fit the properties of biogas. However, the efficiency is not as good as with a stove designed specifically for biogas. Compared to other gases, biogas needs less air for combustion. Therefore, conventional gas appliances need larger gas jets when they are used for biogas combustion.

Overall efficiency of a stove depends on operating conditions, including temperature, pressure, wind speed, specific heat capacity, bottom and overall shape of cooking vessel, weight and size of vessel, and amount of food to be cooked. Thus different tests for efficiency could yield different results for the same stove.

Biogas requires less air for complete combustion than LPG.  This means that for the same quantity of air, more biogas is required. To achieve this in a stove, the diameter of the jet nozzle should be increased using a drill from 1.2 mm to 1.6 mm, so reducing the output speed of the gas. This will reduce the suction of primary air, which will reduce the amount of air in the mixture.  1.0 $dm^3$ of biogas requires 5.7 $dm^3$ of air for complete combustion, while butane and propane require 30.9 and 23.8 $dm^3$ of air, respectively [Sasse et al., 1991].

Gas stoves can be manufactured by most blacksmiths or metal works. The gas burner is usually made of high quality steel, cast iron or clay. The design of a pot-stand must be sufficiently strong to meet food preparation methods of different communities, for example to allow stirring of thick foods such as millet bread, rice, ugali, injera, matooke and stew.

### *2.4.2 Biogas lamps*

In villages without electricity, lighting is not only a basic need, but also a status symbol. However, biogas lamps currently provide little relief as they are not very energy-efficient and tend to get very hot, releasing excess heat is a by-product. Biogas lamps can be used to generate light by combustion of the gas [Dishna et al., 2005]. The gas lamp consists of gas inlet hole, an air inlet hole, an air inlet adjustment valve, a mixing tube, a fire resistant clay head and gauze mantle. The mantle holder consists of a gas nozzle for the flow of combustible gas and air holes for proper mixing of gas and air. The burning gas heats a mantle until it glows brightly. Reflectors are fitted on top of the lamp, heat and light produced at the mantle are reflected down and the flow of heat through the lamp top is retarded.

The flame from the lamp has to be regulated in such a way that the hottest part of the flame matches the form of the mantle. The air mixture and size of the mantle play the biggest roles in determining the efficiency of biogas lamps. The $CH_4$ content of biogas sometimes changes. Therefore, brightness of the light will also change. The performance of a biogas lamp is dependent on optimal tuning of the gas mantle and the shape of the flame at the nozzle. The mantle should be surrounded by the hottest core of the flame at the minimum gas consumption rate. If the mantle is too large, it will show dark spots; if the flame is too large, gas consumption will be too high for the light-flux yield. The lampshade reflects the light downward, and the glass prevents the loss of heat.

Biogas lamps have a consumption rate of 120 - 150 $dm^3$ $hr^{-1}$, with an average light output of 600 lumens and an efficacy that varies from 0.48 - 0.94 lumens $watt^{-1}$ [Evan M, 1999; Rubab & Kandpal 1996]. A biogas lamp is only 3 percent efficient; most of the energy is lost in form of waste heat, [Werner et al., 1989].

Biogas lamps are controlled by adjusting the supply of gas and primary air. The aim is to make the gas mantle burn with uniform brightness and a steady, popping low sound. This can be checked by placing the glass on the lamp and waiting 2-5 minutes, until the lamp has reached 1,000-1,500 °C; the operating temperature. Most lamps operate at a gas pressure of 0.49 - 1.47 x $10^{-3}$ Pa. If the pressure is any lower, the mantle will not glow; if the pressure is too high (fixed-dome biogas plants) the mantle may tear.

Steps used to adjust a biogas lamp are as follows:

- Pre-control of the supply of biogas and primary air without the mantle, to produce, at the outset, an elongated flame with an extended inner core.
- Fine tuning the flame with the incandescent body in place, to produce an intensely glowing incandescent body, coupled with slight further fine-tuning of the air supply.

Kerosene pressure lamps can also be modified to use biogas. The jet in the kerosene pressure lamps is enlarged and a new mixing pipe is mounted. The gas is connected via the original pump opening. Instead of a consumption rate of 0.09 $dm^3$ $hr^{-1}$ for kerosene, 186 $dm^3$ $hr^{-1}$ biogas is consumed.

Commercially available gas lamps are not optimally designed for the specific conditions of biogas combustion i.e. fluctuating pressure and variable gas composition. The most frequently observed shortcomings are excessively large nozzle diameters and gas mantles, no possibility of changing the injector, and poor means of combustion-air control. Such drawbacks result in unnecessarily high gas consumption and poor lighting.