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Biogas digesters: from plastics and bricks to textile bioreactor– A review

Regina J. Patinvoh[a,b], Joseph V. Arulappan[c], Fredrik Johansson[d] and Mohammad J. Taherzadeh[a]*

[a] *Swedish Centre for Resource Recovery, University of Borås, 50190 Borås, Sweden.*
[b] *Department of Chemical and Polymer Engineering, Faculty of Engineering, Lagos State, University, Lagos, Nigeria*
[c] *FOV Biogas, India, Velachery, Chennai-42 , India*
[d] *FOV Fabrics AB, 50113 Borås, Sweden*

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ABSTRACT

Biogas technology and anaerobic digestion is a well-established process for energy generation but there are still technical and economicbarriers to advancement of this technology especially in developing countries. Considering the relatively long retention time of the materials inside the bioreactors, the material of construction of the bioreactor is important for commercial applications and should be selected considering cost, lifespan, effectiveness, design and operation of the bioreactor. The design and operation of particularly householdand smaller bioreactors with their challenges are reviewed in this study. A particular attention is made to the new textile bioreactors that are relatively new in the market. The laboratory and pilot scale results shows that the innovative textile bioreactor is a promising technology for global energy generation advancement

1. Introduction

Renewable energy is gaining wide spread acceptance; renewables accounted for about 62 % of net additions to global power generating capacity in 2016 and majority of renewable heat were supplied by biomass with smaller contributions from solar thermal and geothermal energy (REN21, 2017). Biogas technology has been used quite extensively in developed countries and some developing countries for renewable energy generation thereby reducing greenhouse gases emissions from large volume of wastes generated and continuous burning of fossil fuels. The technology has improved significantly through support from government and non-governmental organizations (Dahlquist, 2013; Geels & Raven, 2007; Nilsson et al., 2012). However, many countries are still under environmental pressures and energy insecurity, which has led to increased interest in biogas technology around the world. This technology is currently the most sustainable way to utilize the energy content of organic wastes while also recycling the nutrients and reducing harmful emissions (Luostarinen et al., 2011). Acceptance of the digestate residue as organic fertilizer, ban of landfilling and the restriction of incineration of organic waste are possible factors favoring the development of this technology around the globe (Torrijos, 2016).

During the last decades, a number of reactors have been developed and examined for small- and large-scale biogas production, but there are still technical barriers for successful operation of biogas reactors which impede the development of this technology. In addition, the cost of many biogas reactors (capital, operational and maintenance costs) is high; most farmers and many developing countries are not financially buoyant to install such reactors despite increased interest in biogas technology. Therefore, improving energy efficiency world wide through biogas technology requires innovative strategies and initiatives to motivate investment in biogas production; this will lead to increased economic growth, environmental safety and national security.

Biogas reactor is at the heart of any process plant; its demand and performance are usually the most important factors in the design of a whole plant; and the performance of the reactor is important for economic assessment of the technology as a whole (Peacock & Richardson, 2012). A suitable bioreactor for biogas production should be easy to operate, effective in producing biogas, easy to install and cost effective in order to promote development of biogas technology. Additionally, for an anaerobic reactor to accommodate high loading rates, basic conditions must be met such as high retention of viable microorganisms in the reactor under operational conditions, sufficient contact between viable microorganisms and the feedstock, high reaction rates, and favourable environmental conditions for the microbial communities in the reactor under the operating conditions (Lettinga, 1995). Consequently, for overall effectiveness of the biogas production process, reactors must be selected putting into consideration the design of the reactor, its mode of operation (Peacock & Richardson, 2012) as well as feedstock composition, amount of feedstock to be treated, desired product and process economy of the reactor (Patinvoh et al., 2017a). A biogas reactor must be well designed since the technical conception of a typical biogas plant is towards achieving an optimum

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* Corresponding Author: mohammad.taherzadeh@hb.se

biogas yield considering the overall economy of the process (Werner et al., 1989).

This work aims at reviewing conventional biogas reactors and challenges associated with them while introducing an advanced textile bioreactorfor biogas production, which is relatively new in the market. Detailed knowledge of the textile bioreactor technology for small- and large-scale biogas plants will contribute to development of biogas technology and aid optimizing its economy.

2. Conventional Biogas reactors

Anaerobic reactors are devices designed for microbial degradation of organic wastes in oxygen-free condition for biogas production; such reactors must be water tight and gas tight. Additionally, biogas reactors must be protected against UV light, chemicals, corrosive gases, and insulated against extreme weather conditions. There are different types of anaerobic reactors; what is common to them all is that they produce biogas for energy generation and bio-fertilizer for soil amendment in agriculture. They are, however differentiated either by mode of operation, solid content, operating temperature, process stages, reactor design or material of construction. Reactors are designed for small and large scale biogas production; commonly used materials for construction of biogas reactors include steel, stainless steel, bricks, concrete and plastics (Cheng et al., 2013; Cheng et al., 2014a; ISSF, 2012). Major factors for the choice of material are technical suitability, availability, maintenance and cost-effectiveness (Kuria & Maringa, 2008).

The size of the biogas reactor depends on the amount of organic wastes to be treated, site location, demand of natural gas, consumption pattern, and technical skill of staff regarding operation of the biogas plant (Samer, 2012). Small - scale reactors convert organic wastes such as kitchen wastes, animal manure, human excreta and garden wastes to biogas for household and community use; commonly used reactors are fixed-dome, floating-drum and rubber-balloon (Rowse, 2011). Large scale reactors are typically obtainable in developed countries but also gaining interest in developing countries (DeBruyn et al., 2006) due to environmental pollution and energy poverty. These reactors are used for conversion of large volume of wastes such as municipal solid wastes, agricultural wastes, industrial wastes and sludge from wastewater treatment plantto biogas (Werner et al., 1989). The biogas produced is usually fed into public grid (De Mes et al., 2003) for heating and electricity generation; it can also be upgraded and used as transportation fuel or fed to natural gas grid. The most commonly used large scale reactors are plug flow, continuous stirred tank, upflow anaerobic sludge blanket (UASB), and complete mix reactors; these types of reactors are complex in design and operation (usually require skillful personnel).

Search for new technologies to enhance global advancement of biogas technology has led to invention of plastics and textile biogas bioreactors. A short review on conventional biogas reactors and challenges associated with them will advance the implementation of textile-based bioreactors for small and large scale biogas production.

2.1Fixed-dome and floating-drum reactors

A typical fixed-dome reactor consists of a cylindrical or hemispherical chamber constructed underground; it is made of bricks and cement (An et al., 1997; Samer, 2012; Sasse, 1988). It has both mixing and overflow tanks connected to the inlet and outlet valves of the reactor respectively. The biogas produced is collected in upper chamber (fixed gas holder) and as pressure increases due to continuous gas production the digestate is discharged through the outlet to the overflow tank. The use of fixed-dome reactors for biogas production is an established technology in many parts of the world especially in China, India, Nepal, Vietnam, Bangladesh, Cambodia, Pakistan and Tanzania (Cheng et al., 2013; Ghimire, 2013).

Fixed dome reactors are commonly used for rural households because of their long lifespan (Ghimire, 2013). However, the technology is expensive (Pérez et al., 2014), the construction is labor intensive and required skilled supervision (Kossmann et al., 1999). It is also prone to porosity and cracks as a result of atmospheric temperature fluctuations or earthquake. Cheng et al. (2014b) reported only 53% of fixed dome reactors in good operation during a survey of 94 household plants in Nepal; most plants are not functioning well due to plumbing problems, damages at the slurry chamber and cracks in the reactor (Tomar, 1994). Utilization of the gas produced is less effective as the gas pressure fluctuates and possibility of explosion of the fixed gas holder due to excessive biogas pressure (Kuria & Maringa, 2008). Additionally, large fixed-dome plants always require a separate gas holder and an agitator; floating gas holders are sometimes used in cold region which is more expensive (Sasse, 1988).

Floating-drum reactors are similar to the fixed-dome reactors in operation; the major difference with floating drum reactor is the floating drum on top of the reactor that separates gas production and collection (Shi, 2014). They aremade of mild steel and the reactor walls and bottom are made of bricks; the reactor has a moveable gas holder, cylindrical digestion chamber with the inlet and outlet pipes connected (Kumar et al., 2015). These types of reactors are easy to operate and the drum can provide gas at constant pressure. However, the steel drum is relatively expensive and requires constant removal of rust and regular painting to avoid gas leakage (Kossmann et al., 1999).

2.2 Plastic biogas reactors

Construction of biogas reactors from plastics is an alternative option to solve challenges associated with fixed-dome and floating drum reactors; the technology evolved from the need for new materials that are non-corrosive, good insulator, cheaper and easier to construct (Kumar & Bai, 2005).

Flexible and rigid plastics materials havebeen used for construction of biogas reactors, gas holders, digestate storage and membrane covers; polymeric materials used include polyethylene (PE), polyvinylchloride (PVC), polypropylene (PP), polystyrene (PS), polymethyl methacrylate (PMMA), acrylonitrile butadiene styrene (ABS) and fiber reinforced plastics (Cheng et al., 2013). Several plastic biogas reactors have been developed and tested in countries like China, India Vietnam, Kenya, Bolivia, Bangladesh, Rwanda, Taiwan, Tanzania, Ethiopia, Columbia and Honduras (An et al., 1997; Cheng et al., 2013; Cheng et al., 2014a; GTZ/EnDev, 2010; Nzila et al., 2012; Rakotojaona, 2013). These reactors and challenges associated with them are discussed in subsequent subsections.

2.2.1 Polyethylene tubular reactors

The first plastic reactor was a tubular reactor; an inexpensive red mud PVC reactor of 15 m^3 total volume introduced in Taiwan and evaluated by Pound et al. (1981) using plug flow principles; the content of the reactor was unmixed and unheated. This model was later simplified in Ethiopia and then Colombia (An et al., 1997). Polyethylene tubular reactors also known as balloon tubular reactors were introduced within the project supported by FAO and SIDA (college of agriculture and forestry in Ho Chi Minh City) (An et al., 1994). Since 1990s (Rakotojaona, 2013), several of these reactors have been implemented and commercialized for small scale biogas plants due to low cost and simplicity of installation. Biogas produced is either stored in the upper part of the digester (Nzila et al., 2012) or in a similar rubber tubes made from polyethylene material (Nazir, 1991) and used through the gas vent when required. The first-generation plastic reactors are susceptible to mechanical damage, have short lifespan (2 to 5 years), sensitive to sunlight and deteriorate rapidly due to seasonal changes (Kossmann et al., 1999; Nazir, 1991; Nzila et al., 2012).

2.2.2 Plastic tanks

Rigid plastic tanks are developed for biogas production and they are made of hard polymeric materials such as hard polyvinylchloride (PVC), high density polyethylene (HDPE) and modified plastics except reinforced plastics (Cheng et al., 2013). They are composed of two pre-built rigid plastic tanks (Rakotojaona, 2013); the first tank for anaerobic digestion and the second tank for gas storage. They are easy to install, longer lifespan compared to polyethylene tubular reactors and quick biogas production start-up (3 to 4 days) (Rakotojaona, 2013), but they are expensive and not suitable for large scale biogas plants. Currently there are very few plastic tanks installed.

2.2.3Latest generation plastic reactors

The problem of low reliability (40 %) (Nzila et al., 2012) with the low-cost polyethylene tubular reactors led to modified plastic biogas reactors. Several polyethylene (PE) tubular reactors installed in Kenya were damaged (burst) and as such reactors were modified to PE/PVC; inner layer PE and outer layer UV treated PVC and further strengthen by synthetic mesh to avoid failure due to stress and high pressure(GTZ/EnDev, 2010). The new model of reinforced plastics in China is made of unsaturated polyester resin, gel-coated resin, chopped strand mat and high-quality glass fiber cloth (Cheng et al., 2013). About 200,000 of these modified reactors have been installed in China with volume ranges from 2.5 m^3 to 10 m^3. Reinforced plastic reactors are developed for biogas production in order to make them weather or UV resistant (Kumar et al., 2015) thereby increasing their lifespan. Research has shown that methane content of biogas produced using reinforced plastics is 15.3%

higher than that obtained when concrete reactors are used (Cheng et al., 2013). However, these modified reactors are expensive and floating where underground water lever persist (Cheng et al., 2013).

Reactor covers are used to store gas produced, insulate the reactor and prevent emission of odor and gases such H_2S, CH_4, NH_3, N_2O, CO_2, and volatile organic compound; reactors covers must be able to withstand exposure to moisture, corrosive gases and digestion feedstock (Stenglein et al., 2011). Most floating-drum gas holders are made of mild steel sheets which is prone to moisture-induced rusting while fixed-dome gas holders are susceptible to cracking (Kossmann et al., 1999). There are new reactor covers made from plastics which are different from conventional fixed and floating covers. Plastic covers are mostly made of high density polyethylene (HDPE) (Mostajir et al., 2013), linear low density polyethylene (LLDPE), polyvinylchloride (PVC). Recently plastic covers are made of composites polymeric materials to reduce permeability, reinforced and strengthen the membrane and also to provide protection against UV light and chemicals (Stenglein et al., 2011). The steel drum is recently replaced with fiber reinforced plastics gas holders to solve the problem of corrosion but they are more expensive.

3.Textile biogas reactor technology

3.1 History and development

Plastic biogas reactor technology was introduced to solve some of the problems associated with conventional biogas reactors as discussed in section 2. However, the lifespan of the material is short due to easy degradation and plastic biogas reactors are not robust for large scale application (Chen et al., 2012; Cheng et al., 2013). GTZ/EnDev (2010) also reported several of biogas plants installed failing due to low quality of plastic reactor bags. These shortcomings led to the development of a textile biogas reactor for reliable biogas productionconsidering efficiency, economy and large-scale application of the reactor. This invention aims at making the biogas technology accessible and attractive to several countries especially developing countries that may not have substantial subsidy support for biogas implementation.

This new biogas reactor is made of textiles which makes it less combustible, resistant to tearing, light weight and environmentally friendly. The textile reactor is UV treated to prevent easy disintegration due to exposure to sunlight; they are also insulated against extreme weather conditions thereby increasing lifespan. Additionally, the reactor is composed of sophisticated coated polymers as a protection against corrosive gases such as H_2S. Textile biogas reactors range in size from $1m^3$ to $1000\ m^3$ and they can be used for small and large scale biogas plants treating sludge from wastewater treatment plants, industrial wastes, agricultural and organic fraction of municipal solid wastes.

3.2 Laboratory studies

The first textile biogas reactor developed was of a pyramid shape as shown in Fig.1; it was a continuous reactor with a total volume of about 112 L. The inlet and outlet pipes were fixed on opposite sides of the reactor, the gas outlet was fitted on the upper part and opener fixed to the reactor for discharging the digestate residue when desired. The efficiency of this reactor was investigated by Rajendran et al. (2013) for biogas production using synthetic medium and treating organic fraction of municipal solid waste; the reactor was operated at room temperature. Rajendran et al. (2013) studied the suitability and efficiency of the new reactor since textile material has never been used for constructing biogas reactor. The results showed a stable biogas operation with organic loading rate (OLR) of 1.0 gVS/L/d yielding 570 L/kgVS/d when synthetic medium was used. The same yield was obtained when organic fraction of municipal solid waste was treated with an increasing OLR from 0.1gVS/L/d to 1.0 gVS/L/d; studies showed that the reactor was appropriate for effective degradation of the treated waste. Rajendran et al. (2013) also did the economic evaluation of the process and reported the sum of investment and 15 years operational cost of the reactor to be 656 USD which is a positive investment when compared to 1455 USD for subsidized LPG and 975 USD for kerosene.

A horizontal textile bioreactor was thereafter produced for batch anaerobic digestion processas shown in Fig.2. The reactor had a volume of about 90 L with a gas outlet, air- and water-tight zip for opening and closing the reactor; it was operated at a temperature of 25°C. The reactor could be heated underneath to attain desired temperature in cold regions, but this is not needed for tropical regions (Patinvoh et al., 2017b). The potential of this reactor for dry anaerobic digestion was evaluated by Patinvoh et al. (2017b) treating manure bedded with straw at 22 % to 30 %TS of feedstock. The study further evaluated the technical and economic aspect of the new textile bioreactor for biogas production through dry digestion process. The textile bioreactor operates on simple principleand worked successfully for over 324 days without leakage or major maintenance. Patinvoh et al. (2017b) reported methane yield of 290 NmlCH4/gVS at 30 %TS after long acclimatization of the inoculum. The textile bioreactor can be used over and over again; once a batch has been processed in the reactor, a new batch can be loaded. At the first attempt, the process to convert the waste into biogas took longer time. Subsequent attempt batch processes resulted in increased biogas production and reduced retention time. The results obtained showed textile bioreactor is suitable for biogas production; the reactor can be used effectively in rural areas, by farmers and for large scale applications. Several reactors can be coupled in parallel for continuous wastes treatment resulting into continuous biogas production; number of reactors needed in parallel depends on the feeding rate and degradation time. The digestate residue analyzed showed suitability as bio-fertilizer; this showed there was no reaction between the material of construction of the reactor and the digestate. The economic evaluation on the experimental results also showed dry-AD with this reactor a profitable method of handling the waste with maximum payback period of 5 years, net present value from \$7,000 to \$9,800,000 (small to large bioreactors) with internal rate of return from 56.6 to 19. 3 %.

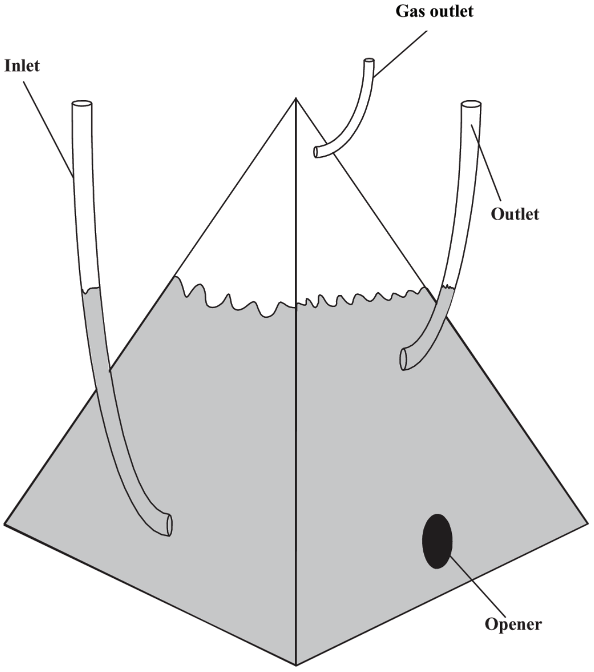

Fig. 1. Schematic sketch of the first generation textile bioreactor (Rajendran et al., 2013)

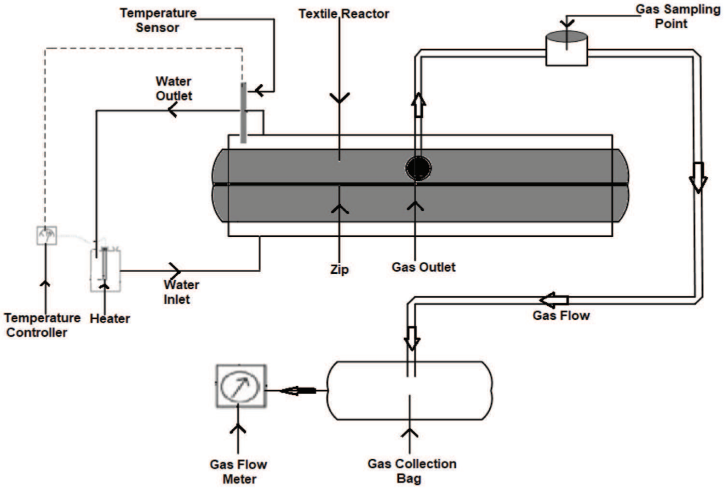

Fig. 2. Schematic sketch of textile bioreactor for dry-AD (Patinvoh et al., 2017b)

3.3 Stress analysis and test for large scale application

A biogas reactor is liable to failure if the gas pressure exceeds a limit that the reactor can withstand; it is therefore important to understand and quantify stress in the reactor (Kaminski, 2005) as a safety measure. GTZ/EnDev (2010) reported some of the plastic biogas reactors installed in Kenya were damaged (burst) due to stress or high pressure in the reactor.

The developed textile biogas reactor is made of unique composite materials to increase the tensile strength of the reactor for large scale application. However, for safety measures the stress associated with this reactor was determined using curvature and numerical analysis by Osadolor et al. (2016); the analysis was performed for large scale application of bioreactors with volume from 100 m^3 to 1000 m^3. The calculated tensile stress in a 1000 m^3 reactor was reported to be 14.2MPa. The result showed that using textile material can increase the tensile strength more than 14.2 MPa thereby preventing failure while also reducing cost.

Pilot scale textile bioreactors with sizes between 10 and 100 m^3 were installed in India and Indonesia respectively (Rajendran, 2015). The strength and pressure of the reactor was tested for large scale application; the reactor was filled up to half of its capacity and elevated to check its strength and pressure holding. The exploration showed the reactor was very resilient as there was no damage to the reactor after the test (Rajendran, 2015).

4 Biogas plant in India

India has a long history in installation of small scale biogas plants but the pace of installation increased after the launching of National Project on Biogas Development programme (NPBD) (Dutta et al., 1997; Tomar, 1995). India has installed over 3 million family size and 4,000 community biogas plants in the past (Khoiyangbam, 2008), family biogas plants is estimated to reach 5.6 million at the end of 2017 and over 6.5 million are expected to be installed in 2022 (Government of India, 2011; York et al., 2017). Cost of installing a biogas plant, maintenance, and reliability are major barriers to wider implementation of biogas technology in India (Surendra et al., 2014). Most commonly used biogas reactors are fixed dome reactors and floating drum reactors of which there has not been much innovation in the design during the past several years. Additionally, these reactors require high technical skill for construction and also prone to leakages. The steel drum is relatively expensive and requires rigorous maintenance; it requires constant removal of rust and regular painting to avoid gas leakage. Since the beginning of National Project on Biogas Development programme (NPBD), surveys conducted in various regions of India showed that the proportion of functioning biogas plants varies between 30 % and 81 % (Bhat et al., 2001; Dutta et al., 1997; Tomar, 1995). Higher functionality only associated with new reactors and recent designs, major defects were technical, operational and incomplete installation (Tomar, 1995). After studying operations of existing reactors and challenges involved, FOV fabrics developed plug flow textile-based reactorswhich are easy to install and operate, cost effective, portable, modular in nature and easy to maintain. FOV fabrics have successfully installed more than 20 textile reactors for biogas production in India treating food wastes, cow dung, human excreta and mixed feedstocks.

4.1 Process Description

Total volume of the textile reactor is about 100 m^3 and the biogas plant operates on continuous process; the complete system of the plant is shown in Fig. 3. Initially the reactor is loaded with inoculum for a start-up and thereafter fed with the substrates. One metric ton (MT) of cow dung (sometimes food wastes) was mixed with 1m^3 of water to make fluent slurry; 2m^3 of slurry was fed into the reactor everyday through the inlet and the same amount withdrawn. Part of the slurry is recycled back along with fresh cow dung as replacement for water; this is done in order to minimize the volume of water used. The retention time of the process is about 30 days and under optimized condition generates about 40 m^3 of biogas per day. Biogas produced accumulates at the upper part of the reactor and flows through the gas vent to a separate gas storage tank and used afterwards for cooking or for power generation using biogas generator. Digestate residue after biogas production is projected to be used as organic fertilizer to improve the quality of agricultural soil thereby generating additional revenue. The projected economic remunerations from the biogas plant are shown in Table 1.

5. Conclusions

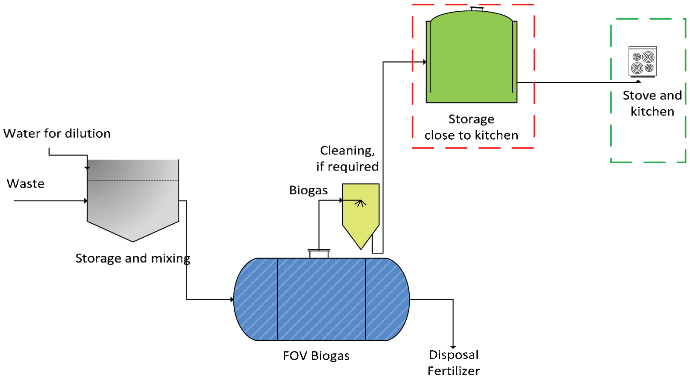

Fig.3. Scheme of complete textile biogas reactor plant in India

Table 1: Economic estimate of products from the biogas plant in India

LPG Savings by setting up a 1 Mt/day of cow dung based textile biogas reactor[a]	
Annual savings on LPG Cylinder	
Number of kg cow dung generated per day	1000
Gas generated (m^3/day)	40
Number of kg of LPG saved per day	20
Savings on LPG per day in Rs	Rs 1, 600
Savings in no. of kg of LPG per year	7, 300
Annual Savings on LPG in Rs	Rs 5, 84, 000
Electricity Savings by setting up a textile biogas reactor[b]	
Annual savings on Electricity	
Number of kg cow dung waste generated per day	1000
Power generated (Kw/day)	40
Savings on electricity per day in Rs	Rs 400
Power generated in Kw annually	14, 600
Annual savings on Electricity in Rs	Rs 1, 46, 000
Savings from organic fertilizer obtained from the reactor	
Annual savings on Organic Manure	
Number of liters of diluted waste fed in per day	2000
Organic manure obtained from bio-slurry per day in kg	160
Savings on organic manure per day in Rs	Rs 800
Organic manure obtained from bio-slurry per year in kg	58, 400
Annual savings on Organic Manure in Rs	Rs 2, 92, 000

[a] *average cost of commercial LPG is considered at Rs. 80 per kg.*

[b] *average cost of electricity is considered at Rs. 10 per KW.*

Bioreactor design for biogas production are getting better in order to reduce cost and construction time of biogas installations; advanced textile bioreactors are promising technology for dissemination. This will enhance global advancement of biogas technology especially in developing countries.

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