

Biogas technology for developing countries

An approach to sustainable development

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Introduction

Non-conventional, easily available energy sources like waste from animals and agricultural residues has attracted the attention of developing and underdeveloped countries due to the energy crisis, which prompted a steep rise in fuel prices. The current disposal practices for agricultural residues have caused widespread environmental concern as they represent hindrance to sustainable development in rural areas as well as to national economies (Sheehan, 2009). Environmental contamination has also necessitated identification of environmentally sound and economically feasible technologies for waste management (Prasad et al., 2007a,b). Anaerobic digestion is a versatile, effective and established method that is being used world-wide for the digestion of different organic wastes and the production of energy in the form of biogas (Verstraete et al., 2005). Organic waste materials of agricultural, industrial and municipal origin can be converted anaerobically into biogas by the action of rumen-derived microorganisms. This technology has the potential to reduce greenhouse gas emissions, because methane as a main constituent of biogas would otherwise be released into the atmosphere, provoking a greenhouse effect that is 21-fold that of the same volume of carbon dioxide. Apart from this, biogas being a cost-effective and environmentally sound energy source helps in improvement of livelihood and promotes sanitation and a healthier household environment in rural areas. Biogas technology also improves rural livelihoods as it is a cleaner fuel than traditional fuels like wood and fossil fuel and can be used for cooking, lighting and heating.

Energy scenario in developing countries

Traditional fuels like wood, charcoal, agricultural residues and animal wastes are major contributors to household energy supply in many of the developing countries having agrarian economies (FAO, 2005). Thornton et al. (2002) reported that the livestock sector directly supports the livelihoods of 600 million poor smallholder farmers in the developing world. Many tonnes of manure from this sector (cattle, buffalo herds, etc.) are produced per day.

This was often used as fertilizer but, due to shortage of firewood, is increasingly dried and used for cooking fuel. About 2 billion people globally use biomass for cooking and heating (Anon, 2005).

Li et al. (2005) compared the total energy usage in 15 least developed countries (LDC) and developed countries and found that 30–95 per cent of energy use was for household consumption, especially for cooking in LDC, which is 25–30 per cent more than that of developed countries. India uses half of its total energy consumption for cooking, of which 87 per cent was from non-commercial fuels such as firewood (Bhatt and Sachan, 2004). Similarly in Yunnan province of China, household energy accounts for 64 per cent of the province's total energy consumption and 55 per cent is from traditional biomass fuels such as firewood and straw (Li et al., 2005). Similarly, an average household in Pakistan depends on biomass for their energy needs, typically using 23–25 kg of firewood, 14–80 kg of dung or 11–60 kg of crop residues (Mirza et al., 2008). But this energy use is often associated with many environmental, health and social problems.

Negative impacts from usage of conventional energy sources

Methane contribution to GHG

Methane is a potent GHG, contributing 17 per cent of total GHG emissions. With a global warming potential of 21 over carbon dioxide, its concentration has increased by 150 per cent to 1800 ppm since the 1750s and accounts for 20 per cent of total radiative forcing (IPCC, 2001, 2007). 590–880 million tons of methane is released worldwide into the atmosphere through microbial activities from the decomposition of biomass (GATE and GTZ, 2007a). On a regional basis, Asia was reported to be the major methane emitter in 2005; China, India, the United States, the European Union and Brazil were the top five methane-emitting economies (Climate Analysis Indicators Tool (CAIT) Version 6.0, 2009). China and India contributed 853 Tg (13 per cent of the world total) and 548 Tg (9 per cent of world total) CO₂e, respectively. Agriculture is the leading source of GHG emissions in the world, contributing around 14 per cent of the total. The primary sources of agricultural GHGs emissions are livestock (particularly cattle, poultry and pigs, which contribute 37 per cent of human-induced methane emissions) and the cultivation of rice paddy (FAO, 2006). Methane emission from enteric fermentation accounts for 16 per cent of the world's annual methane emissions (Tyler, 2007). GHG emissions by India currently comprise 55 per cent CO₂, 23 per cent methane and 22 per cent N₂O. Though the agricultural sector of India contributes only 1 per cent to the country's total CO₂ emissions, it dominates in methane (5 MMT, i.e. 50 per cent) and N₂O emissions (0.31 MMT). The country has a livestock population of around 500 million (with an expected growth rate of 1.23 per cent), accounting for 15 per cent of the global livestock population on 2 per cent of the world's geographical area (Steinfeld et al., 2006).

Methane emissions from livestock wastes

As stated above, livestock contributes 17 per cent of global GHG emissions and 37 per cent of anthropogenic methane. Two factors affecting methane emission from livestock manure are the amount of manure produced (i.e. average amount of manure produced per animal and the number of animals) and the portion of the manure that decomposes anaerobically (which depends on the manure management system used and the climate – primarily temperature).

More than 230 million metric tons of carbon dioxide equivalent (MMT CO_2e) of methane emissions, roughly 4 per cent of total anthropogenic methane emissions, were contributed by livestock manure in 2005, of which 40 per cent was derived from swine, 20 per cent from non-dairy cattle, and 20 per cent from dairy cattle. Poultry is also a significant source of methane emissions in certain countries. The total estimated methane emissions (including enteric fermentation and manure management) from Indian livestock were 11.75 Tg in 2003 (reported in India's Initial National Communication (IINC) to the United Nations Framework Convention on Climate Change). Enteric fermentation constitutes a major part of the total methane emissions, accounting for approximately 91 per cent, or 10.65 Tg of the total, while manure management of livestock accounts for only 9 per cent, or 1.09 Tg. Cattle and buffalo are the major source of methane emissions (10.9 Tg) compared with emissions from other livestock (0.86 Tg) (Chhabra et al., 2009).

Methane emissions from agro-industrial wastes

Agro-wastes, such as crop debris, and spoilt or discarded produce and agro-industrial wastes, such as seed meal residue after oil extraction, can emit methane from its biodegradable organic fraction, which may even be more readily biodegradable than the organic fraction of manure (Doorn et al., 1997). Anaerobic digestion technology for agro-industrial waste management provides enhanced environmental and financial performance than traditional waste management systems (e.g. manure storages and lagoons) and is very effective in reducing methane emissions. Additionally, it also controls air and water pollution due to the controlled retention of the effluent.

Deforestation

Deforestation is a major source of greenhouse gases, responsible for 17–25 per cent of all anthropogenic GHG emissions worldwide (Strassburg et al., 2009). A large part of the deforestation in developing countries is due to over-consumption of firewood for primary energy and accounts for 54 per cent of the world's deforestation. Apart from its impact on climate change, deforestation is also an important factor in soil erosion and land degradation (Osei, 1993; Gautam et al., 2009). The tribal communities of the North Eastern Himalayan region of India have left more than 50 per cent of the region as wasteland as a result of deforestation for firewood. Biogas is therefore a technology that could help to reduce dependence on wood as a fuel.

Due to deforestation and burning of biomass and dung cake, some essential plant nutrients are lost, leading to the loss of those soil nutrients and soil degradation (Dendukurit and Mittal, 1993). In Taktse province in Tibet, 41.6 per cent of the dung from grazing animals is collected and this puts a heavy load on the already overgrazed fields (Liua et al., 2008).

Health risks

Burning of firewood, dung cakes, straw and agricultural residue without the correct chimney or ventilation systems creates many hazardous particles, which can cause severe health problems. The WHO (2002) reported that indoor air pollution from biomass burning increases the risk of acute lower respiratory infections in children, chronic obstructive pulmonary disease in adults, tuberculosis, low birth weight, asthma, ear infections, and

even cataracts (Bajgain and Shakya, 2005). In sub-Saharan Africa, according to *Renewables 2005*, burning solid fuels caused 1–2 million deaths, comprising 3–4 per cent of total global mortality in 2000 (REN 21, 2005).

The collection of firewood and dung is a time-consuming process (often taking several hours every day with over 5 km travelled) and is generally carried out by women and children (Topa et al., 2004). Lighting provided directly from biomass fuel is a poor light source, particularly for children to study after dark. Time spent collecting firewood also takes up time that could be used for education (Gautam et al., 2009). Biogas can be used as a replacement for these conventional fuels and can help to solve many of the problems associated with biomass fuels.

Properties of biogas

Methane is a colourless and odourless gas. The composition and properties of biogas are given in Table 19.1. Methane is a very light gas and is the only combustible constituent of biogas. The specific gravity of methane is less than petrol, LPG and air, hence biogas will rise and dissipate from the site of a leak, which makes it safer than other fuels. In terms of calorific value, one cubic metre of biogas is equivalent to 5–7.5 kWh energy, 1 lb of LPG, 0.54 L of petrol, 0.52 L of diesel and can produce about 1.63 kWh of electricity (with 32 per cent production efficiency) (Horst, 2000; Asankulova and Obozov, 2007); calculated considering 60 per cent biomethane content (with LHV of biomethane: 9.5–10 kWh/Nm³).

Biogas production technology

As described in previous chapters, biogas is produced by anaerobic fermentation, which decomposes complex organic material (biomass), by four groups of microorganisms under humid conditions. The hydrolysis takes place at the initial stage and the hydrolytic enzymes create a suitable environment for acid-forming bacteria, while intermediate metabolites, i.e. soluble and insoluble monomers, are synthesized. The monomers are then converted into fatty acids with a small amount of hydrogen. The most frequently detected organic acids, propionic and butyric acids, are produced with small quantities of valeric acid. This stage is called acetogenesis (acid formation). Biogas production is a multiple-stage process, shown in Figure 19.1.

Bacteria of genera *Bacteroides*, *Lactobacillus*, *Propionibacterium*, *Sphingomonas*, *Sporobacterium*, *Megasphaera*, and *Bifidobacterium* are most commonly responsible for hydrolysis, including both facultative and obligatory anaerobes. Acid-forming bacteria (acidogens) include both facultative and obligate anaerobic fermentative bacteria, including *Clostridium* spp., *Peptococcus anaerobus*, *Bifidobacterium* spp., *Desulphovibrio* spp., *Corynebacterium* spp., *Lactobacillus* spp., *Actinomyces* spp., *Staphylococcus* spp., and *Escherichia coli*. Acetotrophic methanogens, including bacteria from the genera *Methanosarcina* and *Methanosaeta*, perform the conversion and generate methane and carbon dioxide (Sharma, 2008). The various environmental factors influencing anaerobic fermentation of organic substrates are pH, alkalinity, volatile acids concentration, temperature, nutrient availability and toxic materials. The operational factors include composition of organic substrate, retention time, concentration of the substrate, carbon: nitrogen ratio, organic loading rate and degree of mixing (Khanal, 2008).

Table 19.1 Composition and properties of biogas (Bedoya et al., 2009; Gadde, 2006; Paul and Kemnitz, 2006; Horst, 2000).

| Composition of biogas | |
|-----------------------|--|
| CH ₄ | 50–70% |
| CO ₂ | 25–50% |
| N ₂ | 1–5% |
| H ₂ | 1–3% |
| H ₂ S | 0.1–0.5% |
| Properties of biogas | |
| Specific gravity | 1.21 kg/m ³ |
| Heating value | 20–26 MJ/m ³ (4713–6126 kcal/m ³) |
| Density | 0.72 kg/l |

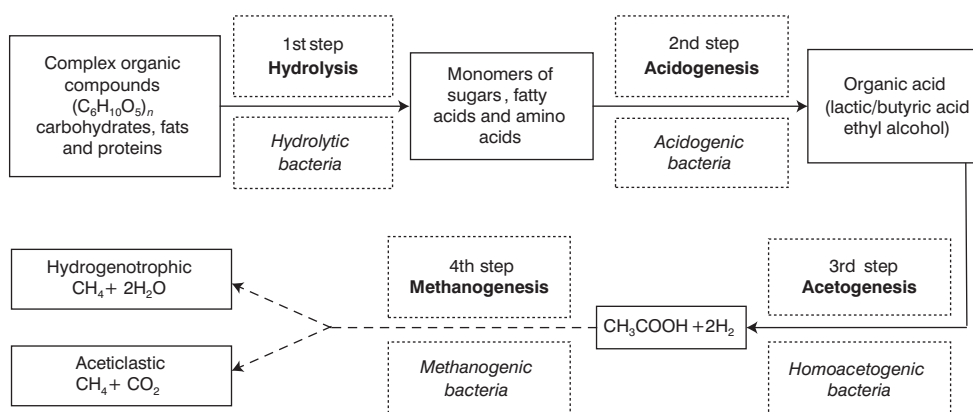


Figure 19.1 Biogas production process

Scope of biogas in developing countries

Biogas can be produced from the organic fraction of biomass like firewood, agricultural wastes and animal wastes which are readily available in developing countries.

Biogas from manures

The advantage of biogas over other fuels is that it requires limited feedstock preparation regardless of the composition and moisture content. The choice of feedstock for biogas depends on its availability. Manures are a widely used feedstock globally (Methane to Markets, 2008). The biogas production potential of commonly used manures is given in Table 19.2. The period for efficient anaerobic fermentation varies with feedstock and for cattle manure, pig manure and poultry manure is 20–30 days, 15–25 days and 20–40 days respectively, considering mesophilic conditions.

Table 19.2 Potential biogas production from different feedstocks (Korres et al., 2010; Singh et al., 2010; Navickas, 2007; Murphy et al., 2006; Murphy and Power, 2006; GATE and GTZ, 2007b; Khendelwal and Mahdi, 1986).

| <i>Feedstock</i> | <i>Biogas yield (m³t⁻¹)</i> |
|--|---|
| Cattle waste | 31–36 |
| Buffalo waste | 54 |
| Piggery waste | 18–55 |
| Poultry waste | 11–35 |
| Human excreta | 20–28 |
| Slaughter waste | 80–156 |
| Organic fractions of municipal solid waste | 125 |
| Used fats | 800 |
| Fatty wastes | 400 |
| Vegetable oil | 350 |
| Distillery waste | 80 |
| Dairy waste | 55 |
| Fruit and vegetables | 35 |

Alternative feedstocks for biogas

The inadequate availability of dung, either due to changes in the size of the cattle holdings of families or its traditional use as farmyard manure and cakes for fuel to meet direct energy requirements, has been a major constraint in the use of biogas. Khendelwal (1990) reported that the availability of cattle waste is capable of supporting only 12–30 million family-size biogas plants against the requirement of 100 million plants. Alternative feedstocks, like herbaceous biomass, used either alone or along with animal wastes for biogas production, are a promising solution to meet the energy requirements of rural areas. A significant portion of 70–88 million biogas plants can be run efficiently with fresh/dry biomass residues. Some reports state 1150 billion tons of biomass is available in India, a fifth of which would be sufficient to meet the Indian energy demand (Jagadeesh, 1996). The potential of many biomass substrates for biogas production were studied by various researchers. The biogas production potential of water hyacinth, *Lantana camera*, castor, neem, groundnut, and coconut were reported (Mallick et al., 1990; Dar and Tandon, 1987; Nagamani et al., 1992). Coir mixed with cattle dung in a ratio of 3:2 gave the best gas output and 80–85 per cent methane content was reported by Radhika et al. (1983). The retention time taken for co-digestion of manure and plant biomass ranged from 50 to 80 days. Co-digestion of biomass often improves the digestibility of the materials, leading to faster and greater biogas yield compared with cattle dung alone. The most important parameters in the selection of particular plant feedstocks are the economic considerations and the yield of methane for fermentation of that specific feedstock (Smith et al., 1992). The biogas yield (m³/kg VS) for leaves, straw and garden wastes were 0.1–0.3, 0.35–0.45 and 0.20–0.50, respectively (Brachtel, 1998; Thomé-Kozmiensky, 1995; Nordberg and Edström, 1997).

The organic fraction of municipal solid waste (MSW), which consists of food waste, paper waste, grass and branches or leaves, is also a good source for biogas generation. Holliger

Table 19.3 Composition of biogas from alternative feedstocks (Naskeo Environnement, 2009).

| Component | Household waste | Waste water treatment plants sludge | Agricultural waste |
|-----------------------|-----------------|-------------------------------------|--------------------|
| Methane (%) | 50–60 | 60–75 | 40–70 |
| Carbon dioxide (%) | 38–34 | 33–19 | 30–60 |
| Nitrogen (%) | 0–5 | 0–1 | 0–1 |
| Hydrogen sulphide (%) | 0.01–0.09 | 0.1–0.4 | 0.3–1 |

(2008) reported the methane production potential of those various organic fraction of MSW were 500, 330, 310 and 110 m³/t, respectively.

Agro-industrial wastes, including hotel wastes, bio-sludge from paper and pulp industry, rejected animal food, fishery by-products, harvest residues and ley crops are other potential source for biogas (Amon et al., 2001). Food processing wastewaters, e.g. from citrus processing, dairy processing, vegetable canning, potato processing, breweries, and sugar production, can also be used for biogas production. Estimations from Global Methane Initiatives (2011) on the total biogas generated from the distilleries, tapioca and corn starch production sectors in India for a period of 7 years (2001–2007), average 1507 million, 187,958 and 635,058 m³/day, respectively. Biogas can even be made from the leftover organic material from other biofuel production like biodiesel (from *Jatropha* seed cake), bioethanol (bagasse, spent wash), etc. Biogas from various alternative sources is characterized in Table 19.3 based on its chemical composition and the physical characteristics.

Domestic biogas plants convert livestock manure and night soil into biogas and slurry (the fermented manure). As discussed in previous chapters, the optimum temperature for biogas production is in the mesophilic range around 36 °C, which makes the technology suitable for most developing countries with (sub)tropical climates (FAO, 1996). The simplicity in implementation and use of cheap raw materials – most easily available in villages – means that biogas technology is one of the most environmentally sound energy sources for rural needs.

Benefits of biogas technology

- **Cooking:** Biogas is used as cooking fuel (see Appendix) in a specially designed burner. Biogas stoves are safe for indoor use and do not produce unhealthy smoke; they thereby reduce healthcare costs and increase productivity.
- **Lighting:** Biogas is used in silk mantle lamps for lighting purposes (see Appendix). The requirement of gas for powering a 100 candle lamp (60 W) is 0.13 cubic metres per hour. Biogas lamps allow households without electricity to light their homes after dark, enabling children to study and family members to increase their working hours. Biogas lamps are brighter than kerosene lanterns and safer for domestic use (Bedoya et al., 2009).
- **Power Generation:** Biogas can be used to generate electricity, especially useful in remote areas that are not connected to the power grid (Urmee et al., 2009).
- **Transport Fuel:** After removal of CO₂, H₂S and water vapour, biogas can be converted to natural gas quality for use in vehicles. Biogas can either be used to operate a dual fuel engine to replace up to 80 per cent of diesel oil, and diesel engines, petrol and CNG engines can be easily modified to run 100 per cent on biogas (Singh et al., 2010, 2011; Korres et al., 2010).

Table 19.4 Energy efficiency of cooking fuels (Barnes and Floor, 1996; Veena, 1988).

| Fuel | Energy (MJ/kg fuel) ^a |
|-------------------------------|----------------------------------|
| Wood | 3 |
| Wood, with stove | 5 |
| Cow dung | 8.76 |
| Crop residue | 15.2 |
| Charcoal, with stove | 10 |
| Kerosene | 12 |
| Biogas | 20–26 |
| Liquified petroleum gas (LPG) | 25–30 |

^a Energy delivered to the cooking pot. Figures are approximate and rounded.

The energy efficiency of biogas as cooking fuel is shown in Table 19.4, derived from a combination of a fuel's energy content and the efficiency with which the fuels are typically burned for cooking in developing countries.

The anaerobic treatment of animal waste through controlled capture of methane and its energetic use means that about 13.24 MMT CH₄/year can be eliminated worldwide. This is mainly acquired by replacing dung with biogas for cooking purposes. In total about 4 per cent of the global anthropogenic methane emissions could be reduced by biogas technology.

The combustion of fossil fuels leads to emission of air pollutants such as CO, NO_x, SO₂, volatile organic compounds and particulates (Parashar et al., 2005). Burning of kerosene, firewood and cattle dung cake as fuels emits 0.8 to 2.2, 0.7 to 4.0 g kg⁻¹ NO_x, and SO₂, respectively along with varying amounts of CO, volatile organic compounds, particulate matters, organic matter, black carbon and organic carbon. Biogas is a smokeless fuel offering an excellent substitute for kerosene, cattle dung cake, agricultural residues and firewood which are used as fuel in most developing countries (MNES, 2006). Burning biogas reduces greenhouse gas (GHG) emissions; it reduces the net CO₂ release and prevents CH₄ release to the atmosphere, a potential means to satisfy various legislative and ecological constraints (Jahangirian et al., 2009). A family size biogas plant substitutes 316 L of kerosene, 5535 kg firewood and 4400 kg cattle dung cake per annum as fuels (Pathak et al., 2009). Substitution reduces emissions of NO_x, SO₂ and CO as given in Table 19.5.

Compared with fossil fuel, combustion of biogas reduces the flame temperature, which reduces NO_x emissions since the main pathway for NO_x formation is thermal (Lafay et al., 2007). N₂O-reduction potential through anaerobic treatment is about 10 per cent, i.e. 49,000 t N₂O/year or 15.7 MMT CO₂-equivalents could be reduced on average (ISAT & GTZ, 1999).

The digester reduces emissions of methane, carbon dioxide and ammonia from manure while in the enclosed vessel. Combustion of the biogas releases some carbon dioxide and sulphur compounds back into the atmosphere. The net saving of GHG for an average-sized biogas plant has been estimated as 4.6 tonnes of CO₂ equivalents per year (Bajgain and Shakya, 2005).

Energy content of biogas compared with other fuels

The amount or volume of biogas is normally expressed in 'normal cubic metres' (Nm³). This is the volume of gas at 0°C and atmospheric pressure. Pure methane has an energy

Table 19.5 Pollution reductions due to use of biogas plant (Prasad and Dhanya, 2011).

| Pollutant | Pollution reduction due to a biogas plant (kg year ⁻¹) | | | |
|---------------------------------------|--|----------|-----------|-------|
| | Kerosene | Firewood | Dung cake | Total |
| Oxides of N (NO _x) | 0.7 | 12.2 | 3.5 | 16.4 |
| Oxides of S (SO _x) | 1.3 | 3.9 | 6.2 | 11.4 |
| Carbon monoxide | 0.6 | 549.6 | 436.9 | 987.1 |
| VOCs | 0.2 | 38.7 | 30.8 | 69.7 |
| Particulate matter ¹⁰ | 0.1 | 16.6 | 13.2 | 29.9 |
| Particulate matter ^{<2.5} | 0.1 | 11.6 | 28.6 | 40.3 |
| Organic matter | 0.4 | 7.2 | 17.6 | 25.2 |
| Black carbon | 0.1 | 3.3 | 11.0 | 14.4 |
| Organic carbon | 0.1 | 19.4 | 55.4 | 74.9 |

Table 19.6 Energy content of biogas compared with other fuels (Asankulova and Obozov, 2007, www.preem.se, www.swedegas.se).

| Fuel | Energy value (kWh) |
|--|--------------------|
| 1 Nm ³ biogas (97% methane) | 9.67 |
| 1 Nm ³ natural gas | 11.0 |
| 1 litre petrol | 9.06 |
| 1 litre diesel | 9.8 |
| 1 litre E85 | 6.6 |

1 Nm³ biogas ≈ 1.1 litres of petrol, 1 Nm³ natural gas ≈ 1.2 litres petrol

value of 9.81 kWh/Nm³. The energy value of biogas varies between 4.5 and 9.1 kWh/Nm³, depending on the relative amounts of methane (50–70 per cent), carbon dioxide and other gases present. Thus, if biogas comprises 60 per cent methane, the energy content is ~6.0 kWh/Nm³. Energy content of biogas compared with other fuels is given in Table 19.6.

Biogas has very high octane number, approximately 130 in comparison to gasoline (90 to 94) and alcohol (105) at best (Paul and Kemnitz, 2006). This means that a higher compression ratio engine can be used with biogas than petrol. The cylinder head of the engine is faced so that the clearance volume will be reduced and the compression ratio can sufficiently increase, thus volumetric efficiency and power output are increased (Biogas Digest, 2010).

Biogas as transportation fuel

Motive power can be generated by using biogas in a dual fuel internal combustion (IC) engine. Air mixed with biogas is aspirated into the engine and the mixture is then compressed, raising its temperature to about 350°C, the self-ignition temperature of diesel. Biogas has a high (600°C) ignition temperature, therefore, in order to initiate combustion of the charge, a small quantity of diesel is injected into the cylinder just before the end of compression. The charge is thus ignited and the process is continued smoothly. Converting a spark-ignition engine for biogas fuelling requires replacement of the gasoline carburetor with a mixing

Table 19.7 Pollution reductions due to biogas used as vehicle fuel (Traffic and Public Transport Authority, 2000).

| <i>Pollutant</i> | <i>Emission (g/km)</i> | | |
|----------------------------|------------------------|--------------------|---------------|
| | <i>Diesel</i> | <i>Natural gas</i> | <i>Biogas</i> |
| Particulate matter | 0.1 | 0.022 | 0.015 |
| NO _x | 9.73 | 1.1 | 5.44 |
| Carbon monoxide (CO) | 0.2 | 0.4 | 0.08 |
| Unburned hydrocarbons (HC) | 0.4 | 0.6 | 0.35 |
| CO ₂ | 1053 | 524 | 223 |

valve (pressure-controlled venturi type or with throttle). A spark ignition engine (gasoline engine) draws a mixture of fuel (gasoline or gas) and the required amount of combustion air. The charge is ignited by a spark plug at a comparably low compression ratio of between 8:1 and 12:1. Power control is affected by varying the mixture intake via a throttle (Biogas Digest, 2010). The biogas used as vehicle fuel presents better characteristics than natural gas (Table 19.7). Some disturbance still appears for the NO_x emissions which are below the EU norms. Gasoline produces 2.44 CO₂e kg/l and ethanol 1.94 CO₂e kg/l (Popa, 2010). Biogas is far better than the natural gas used for vehicles (NGV) in terms of the CO₂, hydrocarbons and CO emissions (Traffic & Public Transport Authority, 2000).

Borjesson and Berglund (2006) analysed fuel-cycle emissions of CO₂, CO, NO_x, SO₂, hydrocarbons (HC), CH₄ and particles from a life-cycle perspective for biogas systems based on different digestion technologies and raw materials and suggested that the overall environmental impact of biogas depends largely on the status of uncontrolled losses of CH₄, the end-use technology that is used, the raw material digested and the energy efficiency in the biogas production chain.

Better fuel efficiency

The efficiency of fuel usage is one of the major criteria in selecting the best solution to the unsustainable use of biomass as energy. Burning of biomass in a traditional stove and dried dung's heating efficiency can be raised from 10–15 per cent to about 25–30 per cent by using better designed stoves which can also save fuel (Li et al., 2005). The heating efficiency of biogas from dung would be raised to 60 per cent (Mirza et al., 2008). The indoor climate will also be dramatically improved as a result of using clean biogas stoves instead of burning firewood, straw and dung cakes.

Health benefits

Biogas can have significant health benefits, especially in rural areas. According to the Integrated Environmental Impact Analysis carried out by the Biogas Support Programme for 600 biogas users and 600 non-users, 4 per cent more non-biogas users have respiratory diseases (Table 19.8) than those who own biogas plants (BSP, 2000). The qualitative information from various household surveys carried out by BSP has revealed that problems like respiratory illness, eye infection, asthma and lung problems have decreased after installation of biogas plants.

Table 19.8 Health benefits of biogas over traditional fuel wood usage (BSP, 2000).

| Disease | Problems in the past (households) | | Present status of households | |
|----------------------|-----------------------------------|----|------------------------------|---------------|
| | Yes | No | Improved | Remained same |
| Eye infections | 72 | 18 | 69 | 3 |
| Cases of burning | 29 | 71 | 28 | 1 |
| Lung problems | 38 | 62 | 33 | 5 |
| Respiratory problems | 42 | 58 | 34 | 8 |
| Asthma | 11 | 89 | 9 | 2 |
| Dizziness/headaches | 27 | 93 | 16 | 11 |
| Intestinal/diarrhoea | 58 | 42 | 14 | 44 |

Pathogen removal

Human and animal waste is loaded with pathogens like *Salmonella*, *E. coli* O157:H7, *Campylobacter jejuni*, *Yersinia enterocolitica*, *Giardia lamblia*, several types of *Cryptosporidium*, etc. Biogas technology helps in improvement of hygienic conditions through reduction of pathogens, worm eggs and flies, compared with other methods of waste disposal. *Salmonella*, *Shigella*, and *Vibrio cholera*, common pathogens in human waste, were completely eradicated by the digestion process. High temperatures and long retention times kill most pathogens. The time period taken for killing principal pathogenic organisms in biogas plants are one or two weeks for typhoid, paratyphoid, cholera and dysentery bacteria (three weeks for hookworm) and bilharzia, tapeworm and roundworm die completely when the fermented slurry is dried in the sun. Thus by linking biogas plants to toilets, families in rural areas and people living in slums in and around cities have been provided with good sanitation facilities and help in securing hygienic conditions (Brown, 2006; Kunte et al., 1998).

Biofertilizer

The open exposure of manure heaps resulted in loss of nutrients, mainly nitrogen, potassium and some phosphorus, through volatilization and leaching (Matsumoto et al., 1997). Biogas technology is effective in manure management, which reduces nutrient losses from the manure. Moreover, biogas spent sludge (BSS), obtained after anaerobic digestion, is richer in valuable nutrients than the animal manure, which has environmental and economic advantages. BSS is a very relevant input to sustainable agriculture which surpasses the negative problems of energy intensive chemical input based agriculture, like global warming, soil erosion, degradation of ground water, biomagnification of pesticides, etc. The recovery of plant nutrients from the biogas plant, via BSS, represents an additional economic return to the farmer using the technology. The use of biogas slurry in proper combination with chemical fertilizer is one of the major steps in integrated nutrient management for sustainable agriculture (Jain, 1993). The concentration of nutrient elements in the residue after digestion are reported to be higher on a percentage dry weight basis than in the undigested material due to conservation of nutrient elements during digestion and gasification. These residues are readily available for growing plants, as well as residual carbon, phosphorous and trace nutrients, and they can thus be returned to the agricultural land as fertilizer and soil-improvement medium (BORDA, 1997). Samuil et al. (2009) suggested that organic fertilizers, if applied rationally to grasslands, can

entirely replace chemical fertilizers. Slurry from 1 kg of digested dung can yield extra nitrogen up to 0.5 kg compared with fresh manure (Sasse et al., 1991). Anaerobically treated biosolids are often more easy to handle and the digestion process is known to inactivate weed seeds, plant pathogens and pests and decrease the amount of phytotoxic compounds in manure (Gunaseelan, 1997). The volume of sludge produced by anaerobic treatment is 80 per cent less than that produced by aerobic treatment processes. By anaerobic digestion technology, plant nutrients, nitrogen, potassium and phosphorus are not removed but rather enrichment occurs, which is an advantage as the effluent can be applied to agricultural fields in place of chemical fertilizer. This can solve problems of soil degradation in areas where earlier dung has been used as a burning fuel and save costs in purchasing chemical fertilizers, creating revenue for the household (Li et al., 2005).

Employment opportunity

Many local jobs are created around biogas projects. By 2000, almost 200,000 permanent jobs were created by more than 2 million biogas plants in India. During 2000–2001 alone, 164 thousand biogas plants were constructed, generating employment to the tune of 5 million man-days (Patel, 2001).

Improvement in standard of living

Apart from these benefits, biogas plants have provided many indirect social benefits, such as reduction in the drudgery of rural people involved in the collection of fuel materials from long distances, reduction in the incidences of lung and eye diseases from cooking in smoky kitchens and an overall improvement in the standard of living. The daily time spent in feeding a small biogas digester could be as little as 15 minutes compared with several hours in biomass collection. Time consumed cleaning pots and other kitchen equipment can also be lowered since biogas does not create as much soot as biomass. Hence people, particularly women and children, would have more time for education when they do not have to spend as much time collecting firewood and other biomass fuels (Bajgain and Shakya, 2005).

Biogas development in developing countries

The anaerobic fermentation of waste products, human excreta and cattle manure, etc. and widespread use of biogas in many developing countries resulted from the problems associated with traditional use of biomass and lack of alternatives such as fossil fuels. Domestic biogas technology is a proven and established technology in many parts of the world, especially Asia. Biogas plants can be made for individual households or for small communities as they are relatively cheap to build, can use existing waste products such as household waste, human excreta and cattle manure, and are a cheap way of generating energy and handling waste products (Gautam et al., 2009). Small biogas plants started to emerge in India in the beginning of the 1950s and have since then spread over many other countries.

The Netherlands Development Organization (SNV) supports national programmes on domestic biogas that aim to establish commercially viable domestic biogas sectors in which local companies market, install and service biogas plants for households. In Asia, SNV is working in Nepal, Vietnam, Bangladesh, Bhutan, Cambodia, Lao PDR, Pakistan and Indonesia; and in Africa in Rwanda, Senegal, Burkina Faso, Ethiopia, Tanzania, Uganda, Kenya, Benin and

Cameroon. Several Asian countries have embarked on large-scale programmes on domestic biogas, such as China and India, Nepal, Pakistan and Bangladesh, due to the thriving population of livestock and agriculture. China, India, and Nepal have conducted the main biogas programmes; all three countries now have large manufacturing industries for biogas plants.

China

China leads the world with 7.5 million household biogas digesters installed and another 750 large- and medium-scale industrial biogas plants. China's extensive biogas programmes began in the 1950s and reached peaks in both 1960 and 1979. Inadequate education and training of households led to technical failures and declining use subsequent to the biogas programme. Since the mid-1980s, a network of rural biogas service centres has been established to provide the infrastructure necessary to support dissemination, financing, and maintenance. The Guangxi project has become a catalyst for other initiatives in the region; 2.73 million biogas tanks have been built in villages, benefiting about 34.2 per cent of the rural households in Guangxi. It is estimated that 7.65 million tons of standard coal and 13.40 million tons of firewood are saved annually in Guangxi because of the use of biogas. In the 1990s, China's biogas strategy was extended to remote communities in west Guangxi, where wood for fuel was in short supply and rural electricity was not available. In 2002, the strategy was a key component of a six-year IFAD-funded project to improve and sustain the livelihoods of poor rural people while rebuilding and conserving natural resources. By 2006, the project had exceeded its target by providing more than 22,600 biogas tanks and helping almost 30,000 households in more than 3100 villages. As a result, 56,600 tons of firewood can be saved in the project area every year, which is equivalent to the recovery of 7470 hectares of forest.

India

The first digestion plant was built at a leper colony in Bombay, India in 1859. Biogas plants in India were experimentally introduced in the 1930s, and research was principally focused around the Sewage Purification Station at Dadar in Bombay. The early plants developed were very expensive and were not cost effective in terms of the gas output. Over the next twenty years, Jashbhai Patel designed and made several small-scale biogas digesters, envisaging farm labourers as the users. Although other individuals and institutions were also designing biogas plants, in 1961 the Khadi and Village Industry Commission chose to promote Patel's design, which, although more costly than other models, was more productive, had a longer life, and required minimal maintenance (KVIC, 1993).

India had a large programme, with about 3 million household plants installed over its potential of 12 million biogas plants. Initial efforts focused on technology development and increased user awareness (MNES, 2002). The Deenabandhu model is a fixed dome biogas-production model popular in India, with a capacity of 2 to 3 cubic metres, constructed using bricks or by a ferrocement mixture. In India, the Ministry of New and Renewable Energy offers a subsidy per model constructed.

The Deenabandhu model is an improved fixed dome model. The entire plant is built with brick in cement mortar. The digester, gas storage chamber and the empty space above the slurry are all provided in the spherical shell. All the slurry displaced out of the gas storage chamber is stored in the outlet displacement chamber as there is no displacement space on the inlet side. The inlet is in the form of a pipe which connects the digester with the slurry

mixing tank. The hydraulic retention time for this design is 40 and 50 days for northern plains and hilly locations, respectively.

Nepal

In Nepal, around 80–85 per cent of the population make their living through agriculture in rural areas and the agricultural sector accounts for 39 per cent of Nepal's GDP. Of the energy used in Nepal, 88 per cent comes from biomass such as firewood and agricultural residues. The household usage of energy accounts for 90 per cent of the total energy. The biogas technology in Nepal has reached the country from India where biogas digesters have been used since the 1950s. The most common type of biogas digester used in Nepal is a small household scale fixed dome digester (Gautam et al., 2009). The potential for biogas plants in Nepal is estimated as 1.3 million, calculated from the cattle population of the country (Bajgain and Shakya, 2005). An independent non-profit organization, the Nepal Biogas Support Programme (BSP) which has been financed mainly by the Netherlands, has been active in Nepal since 1992 and through this programme over 208,000 biogas plants had been installed by 2010, of these 97 per cent are operational. On average, each biogas plant in Nepal replaces 2 tonnes of firewood annually. With over 208,000 biogas plants, around 420,000 tonnes of firewood is replaced by the 103 million m³ of biogas produced annually. The slurry gives 354 thousand tonnes of fertilizer which replaces artificial fertilizer; 6.75 million L of fossil kerosene is also replaced by the biogas. It has been estimated that these biogas plants save around 12,742 ha of forest which corresponds to around 16.86 million trees. On average, each biogas plant reduces CO₂ emissions by 4.6 tonnes annually and together 111 thousand biogas plants reduces GHG by 510,000–600,000 tonnes CO₂e each year as reported by Bajgain and Shakya (2005). With the help of the Biogas Sector Programme, 208,000 biogas plants were installed by 2010, benefitting 1.25 million people across the country and meaning that 420,000 tonnes/year less fuelwood was burnt, resulting in a CO₂ saving of 630,000 tonnes/year (BSP-Nepal, 2002; BSP, 2011).

Pakistan

Pakistan is situated in the south Asian region, covering a total land area of 888,000 square kilometres with a population of 140 million. Pakistan is an agricultural country, more than 70 per cent of the population is involved in agriculture and per capita income is about US\$480. Agriculture accounts for more than 35 per cent of the GDP (Ilyas, 2006). In Pakistan, the company, PAK-Energy Solution, is aiming to install 70,000 biogas plants and have designed and developed the Uetians Hybrid Model, in which they have combined a fixed dome and floating drums; and the Uetians Triplex Model. Both of these designs have been innovated for the first time in the world. Moreover, the Pakistan Dairy Development Company has also taken an initiative to develop this kind of alternative source of energy for Pakistani farmers. Biogas is now running diesel engines, gas generators, kitchen ovens, geysers, and other utilities in Pakistan.

Sri Lanka

In Sri Lanka, biomass accounts for 45 per cent of the country's energy needs and the economy is still largely based on agriculture. Although biogas digesters have been introduced in Sri Lanka since the 1970s, poor design, lack of maintenance skills and insufficient capacity to deal with problems meant that only a third of the 5,000 units installed functioned properly.

The Intermediate Technology Development Group (ITDG) started a project in 1996 to improve the success rate of the units on a national level by setting up demonstration units to help to spread information, restoring abandoned units and training users to operate and maintain them. In addition, individual farmers get help to install biogas units on their farms to make use of the manure from their cows.

Sub-Saharan African countries

In sub-Saharan Africa, most of the existing 2,400 biogas units were installed through donor and demonstration projects. But due to inadequate feedstocks, intensive labour demand, high capital costs, poor technical performance, and lack of water, the technology was not completely successful (Gitonga, 1997; Karekesi and Ranja, 1997). A discussion paper prepared by Winrock International for the Dutch Ministry of Foreign Affairs, reports that as a result of biogas, sanitation could yield benefit-cost ratios (BCRs) ranging from 1.22 to 1.35 and financial internal rates of return (FIRRs) from 7.5 per cent to 10.3 per cent for selected African countries (Renwick et al., 2007).

Other developing countries

In Vietnam, Colombia, Ethiopia, Tanzania, Cambodia (see Appendix) and Bangladesh the polyethylene tubular digester was promoted to reduce production costs by using local materials and simplifying installation and operation of biogas plants. The biogas sanitation systems are in operation in many other countries like Barbados, Bolivia, Burundi, Butan, Cameroon, Democratic People's Republic of Korea, Ethiopia, Georgia, Indonesia, Jamaica, Kenya, Laos, Lesotho, Morocco, Mozambique, Nicaragua, Philippines, Republic of Korea, Rwanda, South Africa, Tanzania, Thailand, Uganda, Vietnam, and Zambia.

Policies for adoption of biogas technology

Renewable energy technologies (RETs)

RETs are energy-providing technologies that utilize energy sources in ways that do not deplete the Earth's natural resources and are as environmentally benign as possible (Renewable Energy Association, 2009). A significant effort has been made to mobilize the resources to realize this potential to power rural development (Bhattacharyya, 2006; Boyle et al., 2006). Reducing rural poverty through rural development is the key requirement to achieving the Millennium Development Goals (MDGs) of the United Nations General Assembly by the year 2015, the connection between clean sources of energy and rural energy access. MDG 7 – ensuring environmental sustainability – promotes RETs as a way of expanding access to these services (World Bank, 2004; United Nations Public–Private Alliance for Rural Development, 2009; United Nations, 2009). The United Nations Development Programme (UNDP) 1997 Report, *Energy after Rio: Prospects and Challenges* identified community biogas plants as one of the most useful decentralized sources of energy supply. Unlike the centralized energy supply technologies, such as power plants based on hydroelectricity, coal, oil or natural gas, that have hitherto been the only choices open to rural communities, biogas plants do not require big capital to set up, and do not pose environmental problems that excite public opposition. They also offer solutions to existing environmental problems, and many unexpected benefits (United Nations, 1984).

Clean Development Mechanism (CDM)

The CDM of the United Nations Framework Convention on Climate Change (UNFCCC) can be used for biogas projects. This flexible mechanism makes it possible for Annex 1 (developed) countries to displace emission reductions to developing countries. The avoided GHG emissions from the CDM projects will generate CERs (Certified Emission Reductions) that can be bought by Annex 1 countries. This can help finance further biogas growth in developing countries (Bajgain and Shakya, 2005). The UNFCCC has set up a Clean Development Fund, and the World Bank has put together a Carbon Finance Unit to allow rich countries, which are pumping more carbon into the atmosphere than is allowed under the Kyoto Protocol, to buy emissions that poor countries prevent through conserving forests or promoting renewable energy (Grubb, 2003). The production of biogas will also reduce the use of fossil fuels, thereby reducing the CO₂ emission. This is in line with the Kyoto Summit Agreement as a carbon-reducing technology (Mata-Alvarez et al., 2000). Nepal's successful biogas programme make the rest of the world pay hard cash for not burning firewood to release carbon dioxide into the atmosphere (BSP, 2010). Nepal's biogas programme is internationally regarded as a model for successful use of alternative energy for the rural Third World. Nepal has now overtaken China and India in the number of biogas plants per capita. As stated previously, each of its 125,000 functioning digesters prevents 5 tonnes of carbon dioxide equivalents from being pumped into the atmosphere every year. This 'saved' greenhouse gas is what rich countries are buying to offset their own emissions, and is worth US\$5 million. This money can be invested back into clean energy that would make Nepal eligible to trade even more carbon offset to rich polluters.

Other policies or programmes implemented by government of India

Policies from the government have a crucial role in the successful adoption of any technology. In developing countries, many biogas support programmes have focused on rural families using animal manure and human faeces as feedstock in order to reduce the use of firewood by providing people with biogas, to improve soil fertility and to reduce indoor air pollution (Voegeli and Zrubuegg, 2008).

National Project on Biogas Development (NPBD)

This project was launched by the Government of India in 1981, leading to about 3.4 million family-size biogas plants installed all over India by December 2002. This is only 28.3 per cent of the total potential (12 million) of family size biogas plants that can be put up in India (Annual report of MNES, 2002). Also, more than 3,380 Community Biogas Plants (CBP), Institutional Biogas Plants (IBP) and Night-soil based Biogas Plants (NBP) have been installed all over the country.

Biogas based distributed/grid power generation programme

In India, with the purpose of promoting biogas-based power generation, especially in the small capacity range based on the availability of a large quantity of wastes (e.g., animal, forestry, agro/food processing, kitchen), the programme was implemented through nodal departments/agencies of the states/Union Territories, Khadi and Village Industries Commission (KVIC),

institutions, and non-governmental organizations in January 2006. The government of India provides subsidies and financial assistance to waste-to-energy projects, especially for households.

National Biogas and Manure Management Programme (NBMMP)

The Central Sector Scheme of the National Biogas Programme in India, which mainly focuses on setting up family-type biogas plants, was implemented in 1981–1982. NBMMP provides subsidies; turn-key job fees linked with three years of free maintenance; financial support for repairing old, non-functional plants; training for users, masons, entrepreneurs, and others; publicity and extension; service charges or staff support; state-level Biogas Development and Training Centres (BDTC); fixed amount of support to institutional biogas plants; and financial support to institutions for cattle dung-based power generation plants. A total of 3.93 million family-type biogas plants have been established in the country, with an estimated potential for 12 million plants.

Problems and challenges

Bioconversion of organic domestic and farm residues has become attractive as its technology has been successfully tested through experience on both small- and large-scale projects. Nevertheless, there are still several problems that impede the efficient working of biogas generating systems.

Technical constraints

It is a very complex technology, requiring the combination of a variety of classical fields of engineering, i.e. of professionals. Highly skilled personnel are required for the installation and maintenance of biogas plants. Improper preparation of influent solids leading to blockage and scum formation, temperature fluctuations, maintenance of pH for optimal growth of methanogenic bacteria, C/N ratio, dilution ratio of influent solids content, corrosion of gas holder, pin-hole leakages (digester tank, holder, inlet, outlet), etc. are some of the technical problems in biogas production and usage. Other technical issues are mostly related to bad maintenance. A common problem is that pipes get blocked due to lack of service and leakage is also a problem that is not unusual with fixed dome biogas plants (Korres et al., 2010; Woods et al., 2006; Bajgain and Shakya, 2005; Han et al., 2008). These problems can be reduced by regular maintenance of the biogas plant.

Financial constraints

Lack of financial capabilities to invest in biogas plants among poor farmers in rural areas remain one of the biggest challenges. Construction costs could be reduced for only slightly higher planning costs. Progress could be enhanced if public funds were available to support small but flexible engineering firms, specializing in anaerobic digestion, rather than large offices, which often stick to known but outdated techniques, because of their high overhead costs.

Social constraints

Social constraints and psychological prejudice against the use of raw materials like night soil also prevents biogas from its wide use (Bajgain and Shakya, 2005). The negative image of biogas production, which was created by the early installations, has considerably reduced the interest of farmers to build biogas plants. In particular, the malfunction of the widely announced, large-scale demonstration units, such as the village biogas plants in Denmark, or the installations erected in agricultural schools in Switzerland, had a detrimental effect on the local diffusion, even though a considerable number of problems arose only due to poor maintenance. The social pressure to build individually-owned installations is lacking (Marchaim, 1992).

Environmental constraints

Most of the digesters in India operate normally at ambient conditions. Northern India records a shortfall in biogas output during winters and in some other parts of the country, especially in dry tracts, which also affect the digester performance due to higher temperature. Cold temperatures will make the biogas plants more inefficient and if the temperature drops below 10°C the whole process will stop. Biogas plants built in areas where temperatures drop below 10°C will need extra insulation and possibly water heating to maintain operation which will add to the construction costs (Bajgain and Shakya, 2005). If there are heavy rains, biogas digesters that are below ground can get flooded and as a result have to be drained, which adds to the maintenance time and costs.

Other constraints

Constraints like cost of cleaning, upgrading (to remove CO₂) and transportation of biomass, limit the use of biogas (Jahangirian et al., 2009). The carbon dioxide and water present in the digester dilutes the energy content of biogas, lowering its calorific value. Hydrogen sulphide is an extremely reactive biogas constituent that forms sulphuric acid in the presence of moisture. The acids formed can corrode engine parts in the combustion chamber, exhaust system, pipelines, storage tank and in various bearings. Therefore, purification to reduce all impurities is a prerequisite for effective biogas utilization as a vehicle fuel.

The lack of effective and clear policies is a major hurdle to overcome in the dissemination of biogas technology. Government has to set policies that promote biogas usage and encourage collaboration with governmental organizations (GO) and nongovernmental organizations (NGO) (Han et al., 2008; Bajgain and Shakya, 2005).

Technical problems can easily be avoided with better site design planning when the biogas plant is built. Public support is very important in the promotion of biogas. It is important to spread knowledge and education about the biogas technology to the people. The government can play an important role to implement pilot biogas projects in rural agricultural areas to showcase the benefits of biogas technology (Ilori et al., 2000).

Use of additives

As discussed in previous chapters, the performance of biogas plant and gas production rate can be improved by stimulating the microbial activity using various biological and

chemical additives under different operating conditions. Agricultural crop residues, e.g. maize stalks, rice straw, cotton stalks, wheat straw, onion storage waste and water hyacinth, each enriched with partially digested cattle dung, enhanced gas production in the range of 10–80 per cent. Powdered leaves of some tree spp. (like Gulmohar, *Leucacena leucocephala*, *Acacia auriculiformis*, *Dalbergia sisoo* and *Eucalyptus tereticornis*) and legumes have been found to stimulate biogas production between 18–40 per cent (SPOBD, China, 1979; Chowdhry et al., 1994). The additives also help to maintain favourable conditions in the reactor (such as pH, inhibition/promotion of acetogenesis and methanogenesis for the best yield, etc.), which helps in rapid and higher gas production (Yadvika et al., 2004). Several inorganic additives that improve gas production have also been reported. Dar and Tandon (1987) reported that alkali treated (1 per cent NaOH for 7 days) plant residues (lantana, wheat straw, apple leaf litter and peach leaf litter) when used as a supplement to cattle dung, resulted in almost two-fold increase in biogas and CH₄ production. Improvement in biomethanation of mango processing wastes by the addition of seed extracts of Nirmali, common bean, black gram, guar and guar gum at the rate of 1500 ppm was also reported by Babu et al. (1994).

Strains of some bacteria and fungi have also been found to enhance gas production by stimulating the activity of particular enzymes (Yadvika et al., 2004). Cellulolytic strains of bacteria like actinomycetes and mixed consortia have been found to improve biogas production in the range of 8.4–44 per cent from cattle dung (Tirumale and Nand, 1994; Attar et al., 1998). The addition of iron salts at various concentrations (50 mM-FeSO₄, 70 mM-FeCl₃) have been found to enhance gas production rate. Shimizu (1992) claimed that high concentrations of bacteria could be retained in the digester by the addition of metal cations since cations increase the density of the bacteria, which are capable of aggregating by themselves. Wong and Cheung (1995) reported that the plant with a higher content of heavy metals (Cr, Cu, Ni and Zn) had a higher CH₄ yield than the control. Certain adsorbents are also reported to improve gas production. Patel et al. (1992), in anaerobic digestion of water-hyacinth cattle dung, found a trend of enhanced gas production with high CH₄ content and lower BOD and COD in effluent with increasing doses of different adsorbents (gelatin, polyvinyl alcohol, powdered activated charcoal, pectin, kaolin, silica gel, aluminum powder, bentonite and talc powder). Using Ca and Mg salts as energy supplements, CH₄ production was enhanced and foaming was avoided (Mathiesen, 1989).

Recycling of digested slurry/slurry filtrate

The recycling of digested slurry along with filtrate back into the reactor has been found to improve gas production. Kanwar and Guleri (1994) reported that about 60–65 per cent more biogas can be produced by simply recycling the digested slurry in 1 m³ plug flow type pilot plants. Some designs use vermiculture to further enhance the slurry produced by the biogas plant for use as compost.

Economics of biogas production

Depending on size and location, a typical brick made fixed dome biogas plant can be installed in the yard of a rural household with an investment of US\$300–500 in Asian countries and up to US\$1400 in the African context. A high-quality biogas plant needs minimum maintenance costs and can produce gas for at least 15–20 years without major problems and

re-investments. A well-maintained digester can pay for itself in one-fifth of that time. The size of the digester can be calculated on the basis of the following formula:

Size of digester (m³) = Fresh manure/day × No. of animals × 2 (for cow/buffalo) or × 3 (for pig) × Retention time (60 days)

Conclusion

Developing countries depend upon biomass for energy, which results in negative impacts on environment and society. In contrast, biogas technology provides clean energy, reduces indoor air pollution, and reduces the time needed for traditional biomass collection. The slurry is an additional bonanza as a clean organic fertilizer that increases agricultural productivity. Thus anaerobic digestion is considered an important component of the global strategy to increase energy security and is environmentally safe by providing an alternative to fossil fuels for sustainable development. It is a suitable tool for developing countries rich in agriculture, particularly the livestock sector, for maximizing the use of scarce resources and provides significant benefits to human and ecosystem health.

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