農業施設23巻2号
1992. 11, 45～54

Review

Biogas production from livestock wastes and its prospects in developing countries

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ABSTRACT

Fuel, feed, and fertilizer are critical resources that often must be imported. Especially for agriculturalists in developing countries, the high cost of these resources and high interest rates create significant economic problems.

These economic problems, the decreased availability of renewable sources of fuel, and the need for pollution control and fertilizer conservation have forced people to look for new sources of these resources. Methane fermentation technology is one alternative that has received widespread interest in developing countries because it converts locally available byproducts into fuel, feed, and fertilizer. Through a microbial process, agricultural waste material and byproducts can be converted into valuable products. This conversion is commonly called biogas from biomass.

This paper discusses the principles of biogas production, how to build digesters, and how to utilize the gas and remaining digester sludge that still contains the fertilizer value.

Keyword : Biogas, Anaerobic digestion, Livestock waste, Digester tank, Economics

INTRODUCTION

The predominant household fuels in developing countries are wood, crop residues, dried animal dung and charcoal. Wood for fuel, however, contributes to deforestation that promotes desertification. Smoke from burning wood is damaging to living environments. It is even worse when burning crop residues. The World Health Organization has concluded that respiratory diseases are the chief cause of mortality in developing countries and that acute respiratory infections are a major cause of infant mortality in the same areas (De Koning et al., 1985). A United Nations study showed that women in Africa grow 70 percent of the food, fetch 80 percent of the fuel and 90 percent of water, process 100 percent of the food and do all of the child care and cleaning (Anderson, 1986). Using biogas for fuel can reduce time and labor for collecting firewood and improve living conditions for the family.

Historical

A history of biogas was given by Maramba (1978) who stated that biogas has been observed and

Received on July 14, 1992

studied since ancient times. After the time of the Romans, the Greeks, and the Chinese, and much later the scientific era, there appears to have been a continuing interest leading to the present degree of utilization of this gas. Maramba noted that one of the earliest to mention biogas was Van Helmont in 1630, in a communication about an inflammable gas emanating from decaying organic matter, swamp gas.

Methane is a well known by-product of sludge digestion in sewage treatment plants (Imhoff and Fair, 1940). For many years in Germany, digester gas was collected and compressed into steel cylinders for use as fuel in municipally operated automobiles (Imhoff, 1946). Plans for designing biogas plants in India were presented by Singh (1971) of the Gobar Gas Research Station, and by Adahaoo (1965) of the Allahabad Agricultural Institute. In recent years, India has become interested in the community sized unit, because the cost of a family-sized floating cover unit is high, amounting to an annual family income. With large units there are economies of scale that can reduce the capital investment considerably. Smil (1977) reviewed biogas production in China and gave plans for a typical digester. Diagrams are given for installations in many countries around the world. Some selected historical ones are shown in Figs. 1 and 2.

In the Philippines, Maya Farms pioneered the use of biogas beginning in 1972. At Maya Farms, the largest farm biogas system in the world provides all of the electric power and heat energy for a 50,000-hog pork production and meat packing complex (Orcullo et al., 1985). Kenya is promoting confinement livestock production (zero grazing) systems in order to better

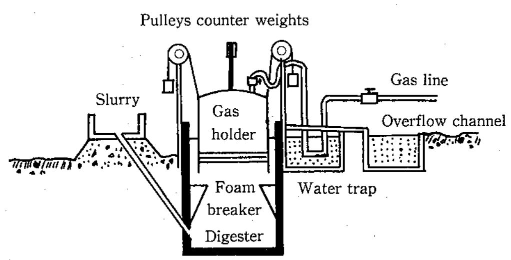

Fig. 1 Gobar gas plant, India Agricultural Research Institute (Maramba, 1978)

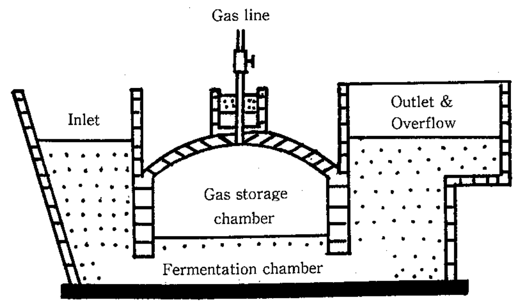

Fig. 2 Biogas plant, China (Maramba, 1978)

utilize land for crops and this allows central collection of fresh manure, which is ideal for biogas technology.

In the Far East, Taiwan pioneered the generation of biogas from swine manure and has been active in this field since the 1960's (Chung, 1980). The digester that has been widely used on small farms consists of a brick-lined earth pit, 1.53m×1.53m, and an inverted steel gas holder, 1.83m×1.83m, 0.92m resting in a water seal. The brick-and-metal biogas unit is getting more expensive and requires considerable labor to build, and the metal gas holders do not last very long. In order to reduce the cost of construction, and to make it possible to build larger units, the concept of a bag-type digester was developed. In 1974, researchers at the Union Industrial Research Institute of Taiwan invented a plastic which is resistant to the ultraviolet rays of the sun. The plastic is termed red mud plastic (RMP). The RMP bag digesters have been used to replace the brick and metal digesters. The bags are mass-produced making possible low-cost methane production on a large scale. The bag can last 10 years under the tropical sun and has been exported to many other countries. Recently, the Taiwan Livestock Research Institute has developed a horizontal tent-type digester which at present is the most economical and simplest digester available (Koh et al., 1988). Compared with the RMP bag digester, it has several advantages. It is easier to construct, has a lower investment cost, and is easy to clean and maintain.

In Japan, increasing confinement of animals results in the accumulation of wastes in limited areas as well as an increase in pollution problems (Haga et

al., 1979). Therefore, the most desirable solution for pollution problems due to animal wastes should involve proper treatment depending on the application of the wastes to land. Maekawa et al. (1984) reported on a two-phase methane fermentation using swine wastes. They found that it became possible to charge higher loadings of organic matter than that of the former conventional methane fermentation, and digested gas production rate was maintained high as the digested gas yield was increased by 20-30%. Takahata et al. (1991) introduced biogas plant in cold region. The mean gas production was about 21/1 digester・day with detention time of 10 days and the net gas production was about 0.61/1 digester・day in winter and 1.21/1 digester・day in summer, respectively.

Anaerobic Digestion Process

Anaerobic digestion (conversion of biodegradable organic matter in the absence of oxygen) produces biogas that is about 60% methane, 40% carbon dioxide and trace amounts of hydrogen sulfide and other materials. Properties of biogas compared to other fuels are given in Table 1.

Table 1. Energy content of various fuels. (Lapp et al., 1978)

Fuel	Energy Content MJ/L	MJ/kg
Propane (C_3H_8)	25.5	50.2
Butane (C_4H_{10})	28.7	49.6
Gasoline	34.8	47.1
Diesel Fuel	38.7	45.6
Natural Gas (99% CH_4)	37.3 MJ/m³	52.0
Biogas (65% CH_4)	24 MJ/m³	33.5
Coal		
Bituminous		32.6
Lignite		14.0
Wood		19.8
Electricity	3.6 MJ/kW	

A review of the theoretical aspects of microbial methane production was made by Bryant (1979). Methanogenesis has traditionally been viewed as a two-stage process, the acid-forming and the methane-forming stages. Recently, however, four-stages have been proposed as shown in Fig. 3. In general, the first

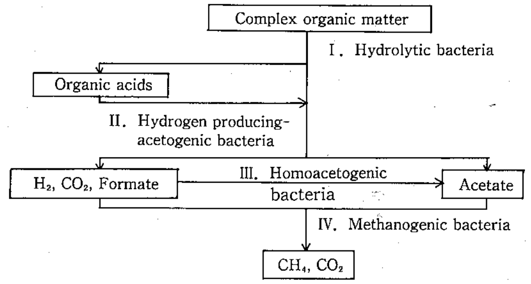

Fig. 3 The four bacterial groups involved in the complete anaerobic degradation of organic matter. (Hashimoto et al., 1981)

stage involves species of fermentative bacteria which, as a metabolic group, hydrolyze complex carbohydrates, proteins, and lipids and ferment their products to fatty acids, H_2 and CO_2. In the second stage, a group of hydrogen-producing acetogenic bacteria produces acetate, CO_2 and H_2 from the fatty acids generated in the first stage. The third stage, called the homoacetogenic bacteria, synthesize acetate using H_2, CO_2, and formate. The fourth stage involves the methanogenic bacteria that utilize the products of the previous stages, mainly acetate, CO_2, and H_2 to produce CH_4 and CO_2. Although the stages are separated for illustrative purposes, the symbiotic nature of the organisms must be emphasized as each group depends upon the others for efficient metabolism.

Several factors must be within appropriate ranges for methane production to occur satisfactorily. These include : pH, temperature, carbon-nitrogen ratio, detention time, and loading rate. The temperature can be such as to encourage mesophilic bacteria or thermophilic bacteria. Thus the digester is referred to as mesophilic (35℃) or thermophilic(60℃). Mesophilic operation in more common for farm digesters than thermophilic because of the additional heat and insulation required to maintain thermophilic temperature.

DESIGN AND CONSTRUCTION

Biogas production occurs in the digester, a tank containing the liquid manure, and facilities for collecting the biogas. The tank must have facilities for feeding the manure, for collecting the gas produced, and for removing digested sludge. In cold climates, the tank should be heated and insulated to reduce heat loss. Some tanks are mechanically stirred and some have only the stirring resulting from liberation of gas bubbles. The objective of stirring is to have intimate contact between the organic matter and the anaerobic bacteria. Stirring is also sometimes used to break up scum that may form on the liquid surface.

There are numerous sizes, shapes and configurations possible for the tank. Some of the more common ones are : vertical above ground, vertical below ground, horizontal above ground, horizontal below ground ; and various other combinations. The size of the tank is determined by loading rate, hydraulic detention time and gas and sludge storage provided in the tank. Published loading rates for anaerobic digesters for manure vary over a wide range (Smith, 1981). Suggested values for farm digesters are given in Table 2. These are based on consideration on VS reduction, NH_3-N levels, stability and heating requirements, and a perceived need to provide simple and easily comprehended guidelines for farm installations.

Table 2. Suggested anaerobic digester operating variables for farm-scale mesophilic (35℃) operation. (Smith, 1981)

Species	Defecated TS %	Influent TS %	Detention time day	Loading rate kg VS/m³·day	Digester volume m³/1000kg	Fractional VS reduction	Methane production m³/m³·day	Influent slurry temp. ℃	Slurry heating m³/m³·day	NH_3-N mg/L
Dairy	12.7	12.7	15	5.7	1.5	0.40	0.9	0	0.23	2600
Beef	11.6	5.8	10	5	1.18	0.45	0.93	0	0.41	2000
Pigs	9.2	5.6	15	3	1.96	0.55	0.72	12	0.18	3000
Poultry	25.2	13.9	40	2.4	3.86	0.55	0.62	12	0.067	5900

India and China Types

A KVIC (Khadi Village and Industries Commission) model of gobar gas plant is the most popular in India and is similar to sewage sludge units in developed countries. The digester which consists of a cylindrical reactor with the ratio of height to diameter between 2.5 and 4.1 produces gas that is trapped under a floating cover and that constitutes a volume of approximately 50 percent of the total daily gas production.

The cover is usually constructed out of mild steel, although other materials such as ferrocement and fiberglass have been used because of corrosion problems. The China biogas plant has a dome-topped chamber which utilizes the lower portion as the digester and the fixed dome as the gasholder. This is by for the most numerous digester operating in developing countries and tends to be operated, at least in China, in two concurrent modes : batch and semicontinuous. Precomposted agricultural residues are normally loaded every six months after the digester has been partially emptied to provide fertilizer for crop planting. Between these batch loadings, swine manure and nightsoil are fed continuously to the digester, and the effluent is removed and used as top dressing. The gas produced is usually stored temporarily in the fixed dome.

Taiwan has developed a long plug-flow digester made of RMP. This has provided an inexpensive, alternative digestion system for use by farmers.

Construction Materials

The tank material can be any common building material such as metal, concrete, rubber, plastic and fiberglass. Major concerns of the tank material are structural strength, corrosion tightness against water and gas leakage, availability, and cost. Most tank materials can be engineered to withstand the water pressures encountered. Leakage can usually be prevented by coating the inside wall. Sievers et al. (1978) used 25 mm of plaster coated with a tar-type compound containing fiber material. Goodrich et al. (1978) coated the inside of their steel tank with asphalt

to reduce corrosion and prevent leakage. Rubber liners, fused on glass, epoxy and several other coatings have also been used.

Collecting and Storage of Biogas

As biogas is produced and rises to the surface, it must be collected in a confined space that is airtight and devoid of oxygen. In cylindrical mixed digesters, this may be a 0.61 to 1.22 m space between the manure surface and the roof structure. The roof is generally the same material as the wall and integral with it may be flat or conical. The plug-flow digester can have a rigid flat roof. However, the internal exposed supporting structure cannot be fabricated from steel due to the corrosive environment of wet biogas. The widely accepted cover for a plug-flow digester is a flexible gas collection bag anchored to the top of the vertical digester walls.

In China, there are four types of biogas storage installations : hydraulic pressure biogas storage tank ; separated floating biogas storage tank ; biogas storage bag ; and RMP cover sheet. Zhang (1989) introduced a new flexible bag with a rolling axis used for biogas storage. This has the advantages of easy manufacture, low cost and guarantees a steady gas pressure for burning. The bag can hang in the kitchen itself, taking up minimal space, and can be operated easily by housewives.

GAS UTILIZATION

Raw biogas can be used for some purposes without cleanup, but removing impurities and concentrating the methane is often desirable. In early times, biogas was commonly improved by filtering it through : limewater to remove carbon dioxide ; iron filings to remove hydrogen sulfide, a highly corrosive gas ; and calcium chloride to remove water vapor. The filters had to be periodically renewed or rejuvenated, otherwise they would become ineffective. Carbon dioxide is removed in industry by a very expensive anode separation scheme. Recent advances, however, using a molecular sieve have brought the cost down to an affordable price. The removal of hydrogen sulfide is possible by scrubbing with water and then exposing the gas to iron oxide ($Fe_2O_3 \cdot 3H_2O$). Koh et al. (1988) reported that the methane content of biogas could be increased to 98% by apurifying process, in which biogas was passed through water in which spirulina was cultured. The water had a pH value of 10-11, and carbon dioxide was thus removed. Methane is not very soluble in water, is highly flammable, and burns with a blue flame. Care must be excercised to prevent the occurrence of methane-air mixtures in the range of 5 to 15% methane by volume since such mixtures are highly explosive.

The most common historic use of biogas is burning it as a fuel to produce heat for domestic uses such as cooking, lighting, heating water, warming homes and warming livestock buildings.

A biogas burner lights instantly, providing smokeless heat for cooking. Thus, using biogas is much more convenient than taking time to light firewood and waiting for the fire to build. There is also the advantage of not wasting heat once cooking is done, since a biogas burner can be instantly turned off. There are similar advantages of using biogas for lighting. While the process of anaerobic digestion is prominently identified with biogas production, it is more appropriate to view the process as a multi-objectives technology. Improving the working conditions of housewives, reducing smoke from burning solid fuels, preventing deforestation and desertification, nutrient conservation, and disease control, are other benefits of biogas technology that should be taken into consideration.

In India and China, burners specifically designed for biogas have been developed, and are manufactured from metal or clay. Both the metal and clay burners

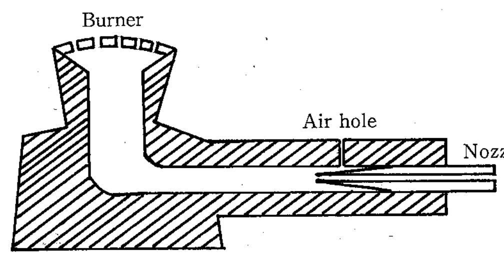

Fig. 4 Biogas burner (Sasse et al., 1980)

can be produced in small workshops. A typical design is shown in Fig. 4. A burner consists of the following basic elements : (1) Injector nozzle, (2) Mixing chamber with air intake, (3) Burner jets, and a shut-off tap. On small burners, the injector nozzle has a diameter of 0.1 to 0.2 mm, and the burner jets a diameter of 1 to 5 mm, depending on the number of jets used. The burner setting depends on gas pressure, so that jet size and in some cases burner shape must be the subject of experiment. Generally, a gas pressure of 5 to 20 cm water column is best for cooking.

Lamps are also quite simple devices as shown in Fig. 5. The construction of a lamp is similar to that of a gas burner : (1) Injector nozzle, (2) Mixing chamber, (3) Porcelain distributor with jets (1.5 mm), a gas mantle, and a shut-off tap. Gas pressure for lamps should be at least 10 cm water column. The best nozzle adjustment must be found by trial and error. Combined lamps and hotplates are very useful items, since they supply both heat and light. Other uses are : fuel for stationary engines for powering such devices as irrigation pumps and electric generators ; fuel for specialized refrigeration units such as the ammonia cycle ; fuel for small mobile vehicles if it is compressed considerably to have a significant amount in a small volume ; and process fuel for alcohol production.

Gas pipe may be made of steel, copper, rubber or

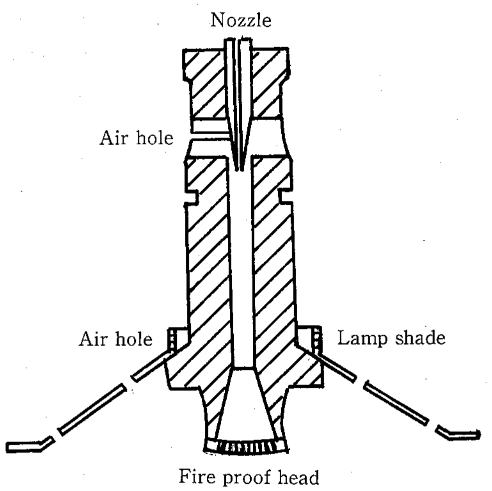

Fig. 5 Biogas lamp (Sasse et al., 1980)

plastics. Rubber hoses quickly become porous and leaky in the sun. The longer the gas pipes the greater the decrease of pressure. The gas pipe must have an outlet for collecting and eliminating water. Table 3 gives a guide to the amount of biogas needed for cooking, lighting and running engines (Sasse et al., 1980).

Table 3. Guide values for gas consumption (Sasse et al., 1980)

Cooking	: 0.25 m^3 (8 ft^3) per person per day
Lighting	: 0.12-0.15 m^3 (4-5 ft^3) per hour per lamp
Driving engines	: 0.45 m^3 (15 ft^3) per HP per hour

ECONOMICS

The economics of farm digesters is very related to price of other fuels and energy ; especially propane, natural gas, and electricity. Since the cost of such fuels and energy has been rising rapidly, the interest in producing commercial fertilizers and feed protein are also important factors. The digester itself is 40-50 percent of the total cost of a floating cover plant and 65-70 percent for a fixed dome plant (Sasse, 1986).

Stewart (1979) reported on the costs of three sizes of digesters. These were \$488/m^3 for a 45 m^3 digester, \$299/m^3 for a 91 m^3 and \$179/m^3 for a 182 m^3, respectively. These included the installation costs but excluded the necessary equipment required to transport the manure to the digester. Huang et al. (1983) assessed the economic feasibility of anaerobic digestion systems. They concluded that the cost of fuel gas ranged between 5.16 and 8.46 NT\$ (0.14-0.22 US\$) on a cubic meter methane basis from estimated capital investments and annual operating costs for alternative processes.

Koh et al. (1988) estimated the total building cost of a tent-type digester at \$60. The shift has been toward using the bag digester which in some cases has been made of imported materials and can be easily installed and used (Chen, 1983). As shown in Table 4, the costs of building an anaerobic digestion system are very site specific.

Fischer et al. (1979) evaluated the profitability of

Table 4. Cost of digesters in several countries.

Country	Installed capital cost (\$)	Reference
China	30/Family-sized digester	Chen (1981)
Costa Rica (Bag digester)	30/m^3	Chacon (1986)
Egypt	50-80/m^3	Ward (1986)
Guatemara (Horizontal masonry digester, cattle)	80/m^3	Ingram (1986)
India	140/m^3	Ward (1986)
Italy (Masonry digester with flexible cover, dairy cow)	295/m^3	Tilche et al. (1986)
Philippine (Maya Farms, swine)	253-533/Vertical digester 307-867/Horizontal 320-840/Fixed dome	Maramba (1978)
Taiwan		
Two digesters, swine	0.14-0.22/m^3CH_4	Huang et al. (1983)
RMP bag, swine	18*	Hong et al. (1983)
Tent-type, swine	60/m^3	Koh et al. (1988)
Turkey	115-160/m^3	Tasdemirogl (1988)
U.S.A.		
Beef-cattle	28-672/m^3	Hashimoto (1979)
	179-488/m^3	Stewart (1979)
Swine	530/m^3	Fischer (1979)

* Economic value of biogas as fuel compared with LPG.

a swine manure anaerobic digester with an internal combustion engine generator system which supplies the electric and thermal energy for a farm in missouri, U.S.A. marketing 3,200 hogs/year. They concluded that the system was profitable with a \$62,375 investment (\$530/m^3 for the digester and \$11,000 for the engine -generator) at a price of electricity \$0.08/kWh and the price of propane at \$0.29/liter. With energy prices of \$0.04/kWh for electricity and \$0.15/liter for propane, the breakeven investment was reduced to \$21,380.

It is emphasized here that an investment in a biogas plant is an investment in a stable source of clean energy and fertilizer.

SOCIAL AND CULTURAL ASPECT

The technical feasibility, economic viability and social acceptability of biogas utilization in rural Egyptian villages were discussed by Capener and El-Halwagi (1986). The pattern of housing animals closely connected to the family house for their care and protection, and the additional dependence on the animals for transportation, draft power, and their products such as milk, meat and hides, attest to the central place that animals occupy in such a system of relationship. In contrast, several biogas plants recently installed on large dairy farms in the U.S. followed U.S. traditional values in its design and installation. That is, there is considerable physical and psychological distance separating the barn from the family house. In the U.S. dairy cows are normally cared for by the men rather than women, and the manure is considered to be dirty and is never handled with one's hands. Thus, the powerful influence of cultural and traditional patterns on fitting biogas technology into flow of existing societal values, beliefs and attitude is recognized.

Although one has to place the digester in a variety of cultural, social, environmental and organizational settings, its feasibility may fare differently in each setting. Capener and El-Halwagi (1986) also made reference to three experimental situations at village level in Egypt which met with differential success, not on their technical soundness but on their social feasibility. In the first case, the small farm household found their biogas plant to have solid technical soundness and a highly satisfactory social feasibility. The second case concerns a second digester placed in the same experimental village, but in this case in connection with a social service center. The technical performance of the digester was highly satisfactory but the social feasibility was very unsatisfactory for a fixed schedule in the center and so on. In the third case, three digesters were judged both technically sound and socially feasible. The third digester itself was proven to be technically sound but failed on social feasibility. An agreement was struck for the two neighboring families to place the digester in a spot where it could receive the waste from both animal sheds. These two families had no kinship ties or bloodline connections. Not long after a successful beginning there began to the questions and suspicions raised among the women as to whether the other family was putting its fair share of manure into the digester or whether some waste was being withheld for other use, and one or the other family was using more than their fair share of the biogas for cooking. Finally an impasse was reached in which the families stopped operating the digester altogether to reduce the level of conflict. As mentioned above, social, ecological and cultural phenomena will have to be considered in designing and installing biogas plants.

CONCLUSION

Much effort has been expended in recent years to apply anaerobic digestion to convert livestock waste to methane. In addition to the energy production, nutrient recycling and pollution control are also benefits of anaerobic digestion. Biogas may be used for cooking, lighting, warming homes and livestock buildings or to run a water pump, water heater, dryer, a refrigerator, automobile or power a generator.

As the digester in the main item of an anaerobic digestion system, the concept of a bag-type or tent -type digester was developed for warm climates in order to reduce the cost of construction, and to make it possible to build larger units. Accordingly, the shift has been toward using the bag digester. It is difficult to assess the economic viability of biogas, even at this stage of its development. Because there is a lack of data from a wide range of conditions and an absence of an agreed on methodology. Where fuels, fertilizers, or feeds are currently purchased, however, biogas may have a good chance of being financially viable.

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開発途上国における家畜糞尿からのバイオガス生産とその展望

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要　旨

燃料や飼料あるいは肥料等を輸入に依存せざるを得ない開発途上国では，これらの輸入がその国の経済に深刻な影響を与えている。また，1970年代のエネルギー危機以来指摘されてきた化石燃料資源の有限性や最近の地球規模での環境保全重視の観点から，エネルギー利用効率の向上，代替エネルギー資源の開発が積極的に推進され，廃棄物の再資源化等も見直されている。

家畜糞尿等を嫌気性消化し，発生するバイオガスをエネルギー源に，また消化液や汚泥を飼，肥料として有効利用できるメタン発酵は，廃棄物の処理のみならず再資源化の方法として，開発途上国では有効な手段と考えられる。ここでは，開発途上国における家畜糞尿からのバイオガス生産，プラントの建設，バイオガスの利用，経済性等について検討する。

キーワード：バイオガス，嫌気性消化，家畜糞尿，消化槽，経済性