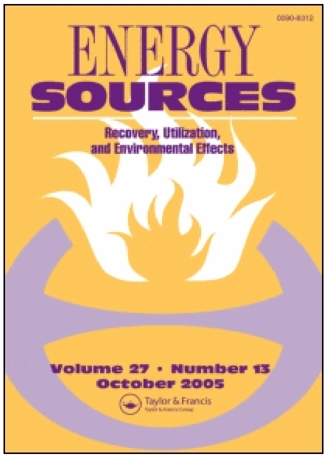

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An Alternative Fuel for Motor Vehicles

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Abstract *The unprecedented increase in oil prices has researchers scrambling for alternative fuel sources. This crisis gives environmentally conscious researchers a new argument in favor of renewable energy. Unfortunately, most renewable energy sources are either inefficient or too expensive. Vehicles around the world are creating a massive environmental problem. Researchers are now looking for an economical and useful alternative to fossil fuel. This article demonstrates that biogas derived from household waste and manure can be used as an efficient fuel source for vehicles. A typical digester design is also shown here. It has been shown that an estimate of biogas production can produce around 1,000 m^3/day in an urban area of around 40,000 population. A comparative statement of biogas production for water hyacinth-cow dung mixture and domestic waste is also shown as a case study.*

Keywords biogas, clean vehicle fuel, digester, natural gas, waste management

Introduction

It is most remarkable that 28% of total world energy consumption is due to transportation. The USA uses almost 66% of its total energy consumption in transportation. So, hydrocarbon fuels used in vehicles are one of the major causes of air pollution and are implicated in global warming and environmental health problems. The dependency of fossil fuel (90 million barrels of crude oil burned per day) has increased the risk of toxic environment around us (Khan et al., 2005a). An alternative to hydrocarbon fuels could improve problems related to municipal landfills and waste management of cities and households by creating a suitable delivery and re-fueling infrastructure. An alternative fuel that is cleaner, free of global warming pollution (GWP), domestically produced, and competitively priced with today's natural gas, diesel, and gasoline is the ideal solution for our health, environment, economy, and national energy security. The price of a barrel of crude oil continues to rise almost daily or is subject to fluctuation. Moreover, a fossil fuel takes millions of years to produce, whereas biogas comes from a constantly renewable resource that can be turned into fuel in three to six weeks. Indeed, the use of biogas does not add to global warming. Biogas can be used by sharing distribution facilities with compressed natural gas as vehicle fuel. Compared with other hydrocarbon gases, this study shows that biogas can be used as a cleaner vehicle fuel.

Natural gas is a combination of methane (>90%), propane, and butane. It is generally found either in crude oil deposits or in stranded natural gas fields. Natural gas can be in the form of compressed natural gas (CNG), liquefied natural gas (LNG), and liquefied

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petroleum gas (LPG). All these are derived from fossil fuel. As such, these gases release greenhouse gases into the atmosphere (Aslam et al., 2006). Researchers (Johnson, 2003; Zhuang et al., 2005) found out that LPG is mainly a mixture of propane with butane and is superior to gasoline and diesel.

Biogas is the mixture of gas produced by methanogenic bacteria while acting upon biodegradable materials in an anaerobic condition. In its raw state, biogas consists of CH_4 (50–70%) and CO_2 (25–50%) and some other gases such as H_2 (1–5%) and N_2 (0.3–3%) (Huang et al., 1998; Singh and Sooch, 2004). It is an odorless and colorless gas that burns with a clear blue flame similar to that of LPG gas. Biogas is about 20% lighter than air. The ignition temperature is in the range of 650°C–750°C (diesel oil 350°C, gasoline and propane about 500°C). The temperature of a biogas flame is 870°C. In this article, biogas is proposed as a fuel for automotive applications. This study is a step in the direction of making a cleaner and environment-friendly alternative upgraded fuel for our daily vehicle use. Kitchen waste/manure and water hyacinth/cow dung mixtures are used as raw materials for biogas production. A comparative study of both the raw materials in biogas production has also been demonstrated.

Recent studies show considerable interest in alternative fuels that can be broadly classified as bio-fuel, advanced bio-fuel, and hydrogen (Yadvika et al., 2004). Conventional bio-fuels are produced from plant crops such as sugar, beet for ethanol, and rapeseed oil or re-processed vegetable oils for bio-diesel. Advanced bio-fuels come from gasified biomass.

Alvarez et al. (2006) studied biogas production from typical manure sources of Altiplano (i.e., llama and cow manures for heat, light, and electricity). They also studied the effects of pressure, temperature, hydraulic retention time, and solid loading, i.e., manure content in the slurry. Dellepiane et al. (2003) studied the feasibility of an electrical power generation process by biogas obtained from sugar cane residues. They examined the availability of the total conversion process of biogas from sugar cane into electricity and the determination of a process solution. Huang et al. (1998) investigated the mechanical and thermal effects on a spark ignition engine if biogas is the driving fuel. They showed how CO_2 (0 to 40%) fraction in biogas plays a role on engine performance and emission control. Their experimental results show that engine performance can be significantly improved if CO_2 content is minimized. Their study was actually designed to observe the performance of exhaust gas emission of a biogas driven engine under different operating conditions. However, they did not show how to use biogas in large scale. Murphy and McCarthy (2005) studied the viability of biogas as a transport fuel on the basis of technical, economic, and environmental perspectives. They identified dry anaerobic combustion process as more efficient than centralized anaerobic digester for biogas production. They did not mention how this biogas should be used as a vehicle fuel based on fuel quality. Prasertsan and Sajjakulnukit (2006) studied the biomass and biogas energy situation in Thailand. They used rice husk, bagasse, oil palm and rubber wood residues, industrial wastewater, and livestock manure. Their aims were to suggest new policy options on resource potential, the promotion program, and its success and failure. Singh and Sooch (2004) studied three models of biogas plant where cattle dung is used. They showed the efficient use of biogas for household applications. They have used anaerobic digester for biogas plant. Islam et al. (2006) have identified the renewable source of energies in Bangladesh and their use. They mentioned almost 17,200 biogas plants functioning efficiently in Bangladesh. A research project has been initiated on biogas production from household wastes (Khan et al., 2005a). However, this study is for household use only. Some European countries, such as Sweden, France, and Netherlands are using biogas as vehicle fuel (Mozaffarian et al., 2004; Rutledge, 2005), but they continue to use fossil fuel for improving the energy content of the gas, which again emits toxic gases in the air. All of the above reviews show that research results in offering replacement for fossil fuel for motor vehicles have been mixed. This article is aimed at providing a definite alternative to fossil fuels as derived from biogas.

A Typical Biogas Plant

The important criteria for a biogas plant construction are the amount of gas required for a specific use and the amount of waste material available for processing. Figure 1 shows a typical biogas plant. The digester is the main component of the plant. Some researchers have designed a complete cycle for heating the digester by using solar energy (Alkhamis et al., 2000). For preheating the digester, a heating coil is used to carry heated vegetable oil that is heated with direct solar heating. This technique has been demonstrated by Khan et al. (2005b). Anaerobic digestion takes place in the digester of the biogas plant.

Criteria for Biogas Production

The efficiency of the biogas production depends on some parameters (Mandal et al., 1999). The plant design is influenced by these parameters (Rutledge, 2005). These are treated as design parameters such as selection of materials for feeding digester, C/N ratio, volatile solid content, loading rate, temperature, pH value, toxicity, dilution, hydraulic retention time, and mixing. Proper design, operation, and maintenance of a continuous digester produce a steady and predictable supply of usable biogas.

i. Selection of Materials. Raw materials may be obtained from a variety of sources described earlier. The selection of materials depends on availability. In a continuous

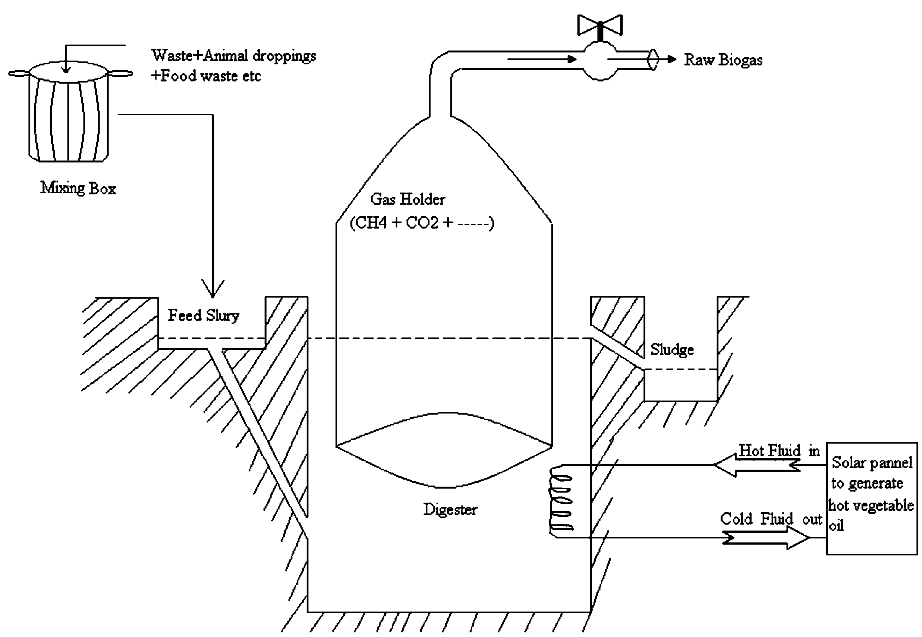

Figure 1. A schematic diagram of a digester plant using solar heat.

digester, organic material is constantly or regularly fed into the digester. The material moves through the digester either mechanically or by the force of the new feed forcing out digested material (Figure 1).

ii. Carbon-Nitrogen (C/N) Ratio. Different literatures have proposed different C/N ratio of waste materials (http://www.lged.org/sre/; Mandal et al., 1999). The bacteria responsible for the anaerobic process require both C and N. They consume carbon approximately 30 times faster than nitrogen. Assuming all other conditions are favorable for biogas production, a C/N ratio of about 30:1 is ideal for the raw material fed into a biogas plant. The range is about 20:1–30:1.

iii. Volatile Solid Content. The weight of organic solids burnt off when heated to about 538°C is defined as volatile solids. In the slurry, this corresponds to a total solids concentration of 8–11% by weight. Anaerobic digestion of organics will proceed best if the input material consists of roughly 8% solids.

iv. Loading Rate (LR). Loading rate is the amount of raw materials fed per unit volume of digester capacity per day, i.e., the rate at which organic material is fed to the digester. LR is based on total volatile solids (TVS) content of the feed, and generally is in the range of 0.15–0.35 lb. VS/ft^{3}d for mesophilic processes. Alvarez et al. (2006) shows how TVS added per day per unit volume of the digester can play a role in the digester.

v. Hydraulic Retention Time. In normal conditions, the time required is almost eight weeks. One third of the total biogas will be produced in the first week, another quarter in the second week, and the remainder of the biogas production will be spread over the remaining six weeks. At high temperatures (45°C–50°C) bio-digestion occurs faster, reducing the time requirement.

vi. Temperature. Mesophilic bacteria works very well at a temperature range of 23°C–38°C. The data were derived from different sources (Alkhamis et al., 2000; Al-Masri, 2001; Yadvika et al., 2004; http://www.lged.org/sre/; Alvarez et al., 2006). All of them discussed the effects of temperature, pH value, and hydraulic retention time and loading rate.

vii. pH Value. A study shows that anaerobic digestion will occur successfully within a pH range of 6.8–8.0. Efficient digestion occurs at a pH near neutrality. More acidic or basic mixtures will ferment at a lower speed. The introduction of raw material will often lower the pH value. Digestion will stop or slow dramatically until the bacteria have absorbed the acids. A high pH will encourage the production of acidic carbon dioxide to neutralize the mixture again. Low pH restrains the growth of the methanogenic bacteria and gas generation.

viii. Toxicity. Wastes and biodegradable residue are often accompanied by a variety of pollutants that could inhibit anaerobic digestion. Potential toxicity due to ammonia can be corrected by remedying the C/N ratio of manure. Common toxic substances are the soluble salts of copper, zinc, nickel, mercury, and chromium. On the other hand, salts of sodium, potassium, calcium, and magnesium may be stimulatory or toxic in action. Pesticides and synthetic detergents may also be troublesome to the process. Mineral ions, heavy metals, and the detergents are some of the toxic materials that inhibit the normal growth of pathogens in the digester.

ix. Dilution. Experience has shown that the raw material (domestic and poultry wastes and manure) ratio to water should be 1:1 (i.e., 100 kg of excrete to 100 kg of water). Before feeding the digester, the excreta, especially fresh cattle dung, has to be mixed with water at the ratio of 1:1 on a unit volume basis (i.e., same volume of water for a given volume of dung).

x. Mixing and Stirring. Stirring the slurry in a digester is always advantageous. If not stirred, the slurry will tend to settle out and form a hard scum on the surface, which will prevent release of the biogas. This problem is much greater with vegetable waste than with manure. It will tend to remain in suspension and have better contact with the bacteria. Continuous feeding causes fewer problems in this direction, since the new charge will break up the surface and provide a rudimentary stirring action. If some form of heating is needed for the bio-digester, this will also provide some circulatory action, which will tend to stir the contents. Agitation can be done either mechanically with a plunger or by means of rotational spraying of fresh influent.

Digester Design

The main component of the biogas plant is an anaerobic digester. This is the device for optimizing the anaerobic digestion of biomass and/or animal manure, which is often used to recover biogas for energy production. Commercial digester types include complete mix, continuous flow (horizontal or plug-flow, multiple-tank, and vertical tank), and covered lagoon. An anaerobic digester is made of concrete, steel, brick, or plastic. They are shaped like silos, troughs, basins, or ponds. It may be placed underground or on the surface. All designs incorporate the same basic components: a pre-mixing area or tank, a digester vessel, a system for using the biogas, and a system for distributing or spreading the effluent (the remaining digested material). Many literatures show a diversity of design for a digester. Figure 2 is a typical digester along with solar heating system. The volume of a digester can be calculated by the following equation (http://www.lged.org/sre/):

$$V = V_C + V_{gs} + V_f + V_H + V_s$$

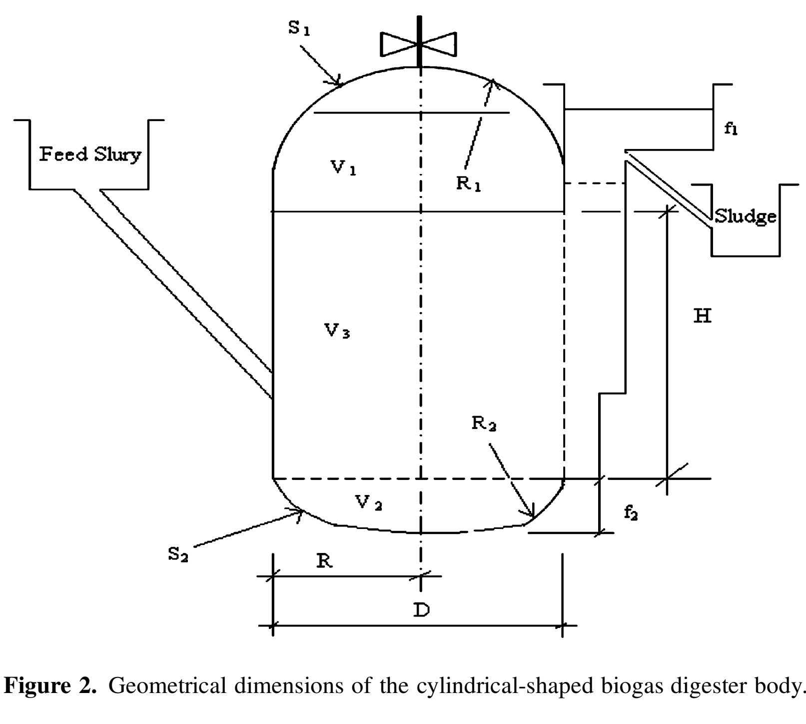

Figure 2. Geometrical dimensions of the cylindrical-shaped biogas digester body.

Table 1
Assumptions for design consideration

For volume	For geometrical dimensions
$V_C \leq 6\%V$	$D = 1.35 \times V^{1/3}$
$V_S \leq 18\%V$	$V_1 = 0.091D^3$
$V_{gs} + V_f = 75\%V$	$V_2 = 0.05D^3$
$V_{gs} = V_H$	$V_3 = 0.305D^3$
$V_{gs} = 0.45(V_{gs} + V_f + V_S)K$	$R_1 = 0.725D$
	$R_2 = 1.125D$
where K = gas production rate per	$f_1 = D/5$
m^3 digester volume per day	$f_2 = D/8$
	$S_1 = 0.9D^2$
	$S_2 = 0.83D^2$

where V, V_C, V_{gs}, V_f, V_H, and V_s represent total volume of digester, volume of gas collecting chamber, volume of gas storage chamber, volume of fermentation chamber, volume of hydraulic chamber, and volume of sludge layer, respectively.

The volume depends on the type of waste, quantity of waste, availability of waste, and output required. For designing a digester, some assumptions are to be made (Adeoti et al., 2000). Table 1 shows these assumptions. These assumptions have been made on the basis of Figure 2. This shows the geometrical dimensions of the cylindrical shaped biogas digester body.

Biogas Production

Any organic (carbon-based) material is a potential source of biomass feedstock to produce biogas. These are some of the most common biomass feedstocks used to produce biogas such as sewage, organic fraction of municipal solid waste (e.g., in landfills), manure (e.g., dairy, pig, cattle), garden waste, forestry wastes, agricultural wastes, energy crops (e.g., clover grass, corn), and industrial food processing wastes (Prasertsan and Sajjakulnukit, 2006). The block diagram of Figure 3 shows the different steps of processing biogas production and the different stages for vehicle fuel. For processing biogas, two basic types of organic decomposition take place. Figure 4 shows the aerobic and anaerobic decomposition. All organic materials, both from animal and vegetable, can be broken down by these two processes. The aerobic process is used for fertilizer. The anaerobic decomposition process is used for producing biogas. It occurs in the absence of oxygen with the following steps (Al-Masri, 2001; Lastella et al., 2002):

$$\text{Hydrolysis} \rightarrow \text{Acid formation} \rightarrow \text{Methane formation}$$

Raw Biogas Collection

The biogas is collected in an inverted drum. The walls of the drum extend down into the slurry to provide a seal. The drum is free to move to accommodate more or less gas as needed. The weight of the drum provides the pressure on the gas system to create flow.

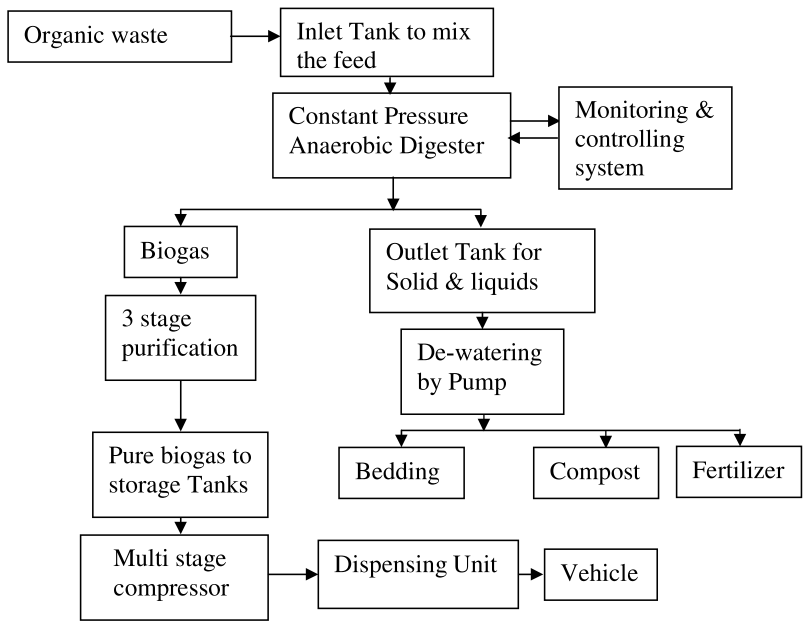

Figure 3. Block diagram of biogas plant for vehicle fuel.

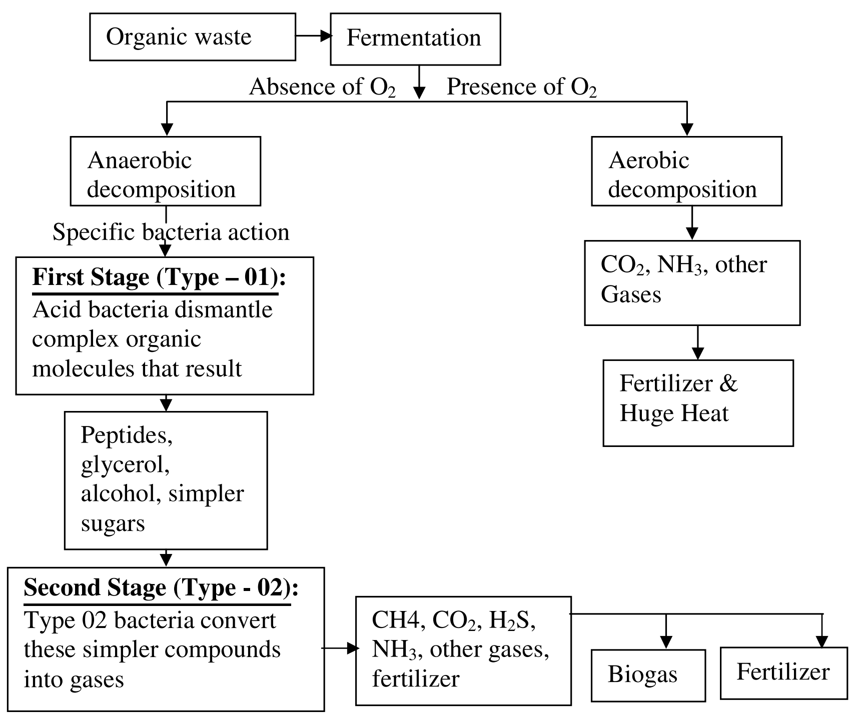

Figure 4. Flow diagram of biogas production.

The biogas flows through a small hole in the roof of the drum (Figure 1). A non-return valve is used to prevent air being drawn into the digester which would destroy the activity of the bacteria and provide a potentially explosive mixture inside the drum. Larger plants may need counterweights of some sort to ensure that the pressure in the system is correct. The drum must obviously be slightly smaller than the tank, but the difference should be as small as possible to prevent loss of gas and tipping of the drum. By using pipeline network, raw gas can be stored in a tank.

By-products from Biogas

The material that comes as a by-product of biogas from the digester is called sludge or effluent. The sludge is very rich in nutrients (ammonia, phosphorus, potassium, and more than a dozen trace elements) and high in nitrogen. It is practically odorless and is an effective fertilizer. Sludge makes a good fertilizer and dietary supplement to cattle and poultry feed. The washed-out fluid can be disposed in a tank to be reused for fish cultures, irrigation, and water plants, etc. When purification of biogas (Figure 5) is done through limewater, high grade limestone is formed. Any toxic compounds (pesticides, etc.) that are in the digester feedstock material may become concentrated in the effluent. Therefore, it is important to test the effluent before using it on a large scale.

Estimation of the Biogas

At present, CNG gas cylinders with a capacity of 10–15 m^3 are available at market. Gas is compressed at a pressure of 3,500 psi in the cylinder. The car can travel more than 100 km with a 10 m^3 of compressed biogas when it is upgraded into almost 98% CH_4. One m^3 biogas equals 5,200–5,900 kcal of heat energy which is equivalent to almost 6.0 liters of diesel fuel or 4.5 liters of gasoline. Table 2 shows details of biogas yield.

Case I (Domestic Waste). Different sources give different values for biogas production based on per amount of organic input (Khan et al., 2005a). For this calculation, it is assumed that methane containing 60–65% gives 0.34–0.49 m^3 gas produced per kg food waste (dry basis). An urban area of 40,000 inhabitants is used as a prototype. These inhabitants are assumed to produce 1.25 MT of kitchen waste. It is noted that fresh water is not compulsory for making slurry. Sewage water can be used for this input which will be more cost effective. This is also environmentally good and municipal-waste management friendly.

Case II (Water Hyacinth and Cow Dung Mixture). There are some studies reported about uses of water hyacinth and cow dung mixture in biogas production. The different studies show different percentage of biogas production based on per amount of water

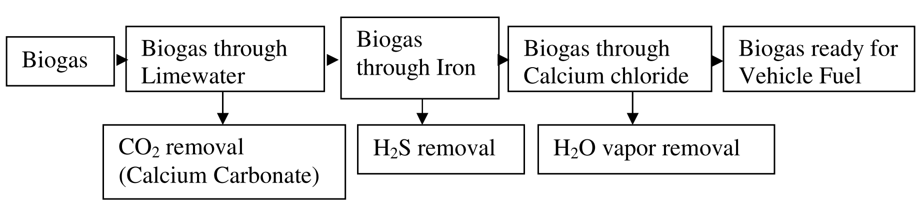

Figure 5. Purification steps of biogas for vehicle fuel.

Table 2
Biogas yield form domestic waste and water hyacinth-cow dung mixture

Items	Case I	Case II
Basis	⇒ 12,500 kg kitchen waste/day ⇒ 2,000 kg feces/day; [0.050 kg (dry)/person/day]	⇒ 531.00 kg of wet water hyacinth (i.e., 26.55 kg dry water hyacinth) ⇒ 227.57 kg cow dung (i.e., 182.00 kg dry cow dung) ⇒ Mixture ratio of the water hyacinth shoots and cow dung is 7:3 ⇒ Mixture ratio of one liter water hyacinth-cow dung and water is 1:3
Total solids (TS) in %, wt/wt	8	6 for water hyacinth and 8 for cow dung
Volatile solid (VS) of TS in %, wt/wt	75	15.4 for water hyacinth and 75 for cow dung
Biogas yield, m^3/kg-vs	0.34–0.49	0.55
Methane content in % (vol/vol)	60–65	75
Retention time	40 days	90 hrs
Calculation for biogas		
Total solid content, kg/day	= 12,500 kg kitchen waste × 0.08 + 2,000 kg feces = 3,000	= 531.00 kg wet water hyacinth × 0.06 + 227.57 kg cow dung × 0.08 = 50.07
Volatile solid content, kg/day	= 3,000 kg of TS × 0.75 = 2,250.00	= 531.00 kg × 0.06 × 0.154 + 227.57 kg × 0.08 × 0.75 = 4.906 + 13.654 = 18.56
Biogas yield, m^3/day	= 2,250.00 kg of VS × 0.45 m^3/kg of VS = **1,012.5**	= 18.56 kg of VS × 0.55 m^3/kg of VS = **10.208**
Biogas yield considering dry waste (m^3/kg)	**0.07**	**0.049**
Status after purification		
Biogas, 65% CH_4	1,012.5	—
Biogas, 75% CH_4	—	10.208
Biogas, 98% CH_4, equivalent to CNG, m^3/day	992.25	10.00
Biogas ready for vehicle, m^3/kg	**0.0684**	**0.048**
Water requirement		
Basis	6% slurry as influent	Slurry ratio is considered as 1:3
Calculation	The weight of slurry = 3,000 kg TS/0.06 = 50,000 kg Wet weight of waste = 3,000 kg TS/0.08 = 37,500 kg Daily water input = 50,000–37,500 kg = 12,500 kg	The weight of slurry = 50.07 kg × 4 = 200.28 kg Daily water input = 200.28–50.07 kg = 150.21 kg
Total, m^3	12.5	0.15

hyacinth and cow dung mixture with water as an input. Water hyacinth consists of 94–95% water and hardly contains 5–6% of total solids by weight (Ganesh et al., 2005). Table 2 shows biogas yield from waste water hyacinth and cow dung. For this estimation, a ratio of 1:3 for water hyacinth-cow dung and water has been considered to make an effective production (Kivaisi et al., 1998; Mwadamwar et al., 1990). It is also assumed that methane containing 70–75% gives 0.50–0.55 m^3 gas produced per kg (dry basis) of water hyacinth-cow dung mixture. An area where cow dung and water hyacinth are available is considered as the potential sustainable project for a family size biogas plant for a car. To produce 10 m^3 of CNG equivalent biogas, only 531.00 kg of wet water hyacinth and 227.57 kg cow dung mixture are needed (Table 2). In this method, no extra water input is required because wet water hyacinth contains almost 95% water and 5% solid.

Purification of Biogas

Raw biogas is typically 50–70% CH_4 and 25–50% CO_2. For vehicle fuel, CH_4 and CO_2 should be 97–99% and 1–3%, respectively. Raw biogas contains a large proportion of CO_2 along with water vapor, some ammonia, some hydrogen sulphide, organic silicon compounds, and a few traces of other gases which are insignificant for practical purposes. Typical natural gas pipeline specifications require a CO_2 content of less than 3%. Vehicle fuel specifications require a combined $CO_2 + N_2$ content of 1.5–4.5%. CH_4 content of the gas is directly proportional to its energy content. These impurities are harmful to the natural gas grid, appliances, engines, other equipment, or end-users. Therefore, biogas needs to be preprocessed, i.e., purified in an operation which is called scrubbing (Mozaffarian et al., 2004; Rutledge, 2005). Figure 5 shows the different steps of upgrading of raw gas by flow diagram.

CO_2 Removal

To increase the calorific value of the gas, removal of CO_2 is obvious for increasing the relative CH_4 content. To extract CO_2, raw biogas is passed through limewater ($Ca(OH)_2$) spray tower (Figure 5). This technique is available in literature (Mozaffarian et al., 2004; Rutledge, 2005). However, membrane systems are highly applicable for separation of gases from a mixture (Basu et al., 2004). They surveyed other available techniques for CO_2 separation including some that are environmentally friendly.

i. H_2S Removal. Basu et al. (2004) introduced an environmentally friendly technique, replacing all available hydrogen sulphide removal processes. They pointed out that those techniques are not environmentally friendly. Therefore, they suggested a series of natural additives, including vegetable oil, for removing H_2S. These processes are more suitable techniques.

ii. H_2O Removal. A vehicle fuel requirement is very strict on H_2O content and dew point temperature. CNG vehicle fuel standards require a dew point of at least 10° below the 99% winter design temperature for the local geographic area. The removal of H_2O can be performed using a number of different methods at varying points in the biogas upgrading process. Refrigeration, adsorption, and absorption are some of the most common methods used for removing the H_2O from biogas. For collecting water vapor, the gas can also be passed through calcium chloride (Figure 5).

iii. Removal of Other Contaminants. A number of effective, commercially available technologies exist to reduce or eliminate the contaminants including filters, membranes, activated carbon, and other absorption media. Recently Khan and Islam (2007) proposed a new line of natural products that can remove these contaminants.

Storages and Ready-for-vehicle Fuel

The upgraded biogas is stored in a tank and compressed before using the vehicle. Compressed biogas is now basically equivalent to CNG. The main difference is that CNG is made by compressing natural gas (a fossil fuel), whereas compressed biogas is made by compressing digester raw biogas, a renewable fuel. Compressed biogas storage requires a gas compressor, storage bottles, safe storage tank, and safety areas plus a scrubber to remove unwanted gas impurities. This latter one results in vastly extended engine life and reliability due to lower operating stresses and fewer corrosive exhaust gases.

Conclusions

In this study, it has been shown how biogas can be used as vehicle fuel. It can be also used like any other combustible gas. Biogas has some significant benefits such as: emitting no greenhouse emission and burning at a slow flame-propagation rate; improving health and reducing respiratory elements; reducing depletion of solar nutrients; better management of animal dung and human excrement; reducing ground water pollution and increasing surface water quality. It can be burnt in stoves, lamps, and motors, or used to produce electric power or pump water. Throughout Europe, in response to EU legislation to cut the amount of organic waste placed in landfills by 35% before 2015, anaerobic digestion is being used to turn organic waste into biogas, natural fertilizers, and small amounts of sanitized compost. Considerable benefits, environmental and otherwise, can be gained through the proper development of a biogas system.

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