POTENTIAL OF BIOGAS TECHNOLOGY USING DIFFERENT BIOMASSES IN DEVELOPING COUNTRIES

Qaisar Mahmood[*†] &
Fayyaz Ali Shah[*]

ABSTRACT

Developing countries are facing critical energy crises. Ever-increasing prices of fossil fuels have resulted in serious impacts on the lives of common people in many developing countries. The environmental phenomena are being seriously affected consequent to increased use of fossil fuels. The renewable energy offers better choice as it is clean source of energy. In view of the limited supply of fossil fuels, biofuels have been considered as future fuels. The demand of biogas technology is increasing and various researchers are trying to improve it. These are low-cost systems and can be run with very small budget. An increased focus is being placed over the use of anaerobic treatment for a number of reasons, including; energy recovery; minimizing the harmful effects of suspended solids; cutting down the cost of waste treatment to almost half over aerobic systems; resultant digestate to be used for land farming; and its compactness as a treatment system. This review focuses on the low cost bioenergy sources in developing countries of the world. Various practical aspects of biogas generation and factors influencing it have been presented. The potential of various biomasses, especially algal biomass, has also been discussed.

Keywords: *Anaerobic digestion, Biogas, Bioenergy, Biomasses, Developing countries.*

1. INTRODUCTION

This manuscript reviews the potential of various biomasses in the production of biogas, which can contribute towards meeting the present energy needs. The world is facing critical shortage in energy supplies. Ever-increasing prices of fossil fuels have resulted in serious impacts on the lives of common people in many developing countries. Increased fossil fuel burning has caused tremendous damage to the environment in terms of global warming; however, biogas technology is green technology that doesn't release green house gases and therefore does not contribute much to the global warming. Biogas comprises 80% of the total renewable energy and it is 10% of the global energy demands (IEA Bioenergy, 2009). Climate change caused by the GHG emissions due to burning of fossil fuels is an associated problem. Climate change is being perceived as a serious phenomenon evident by the severe weather patterns in many parts of the world. Energy shortage and climate change are one of the main challenges of the 21st century, and currently scientists are looking for many alternatives to fossil fuels that can help mitigate these challenges.

The first decade of 21st century has witnessed substantial increase in the fossil energy use. Being rational, such unlimited demand of fossil fuels cannot be fulfilled. The world population continues to grow and, over the next 40 years, agricultural production will have to increase by some 60% (FAO, 2011). Consequently, the energy demands are also expected to rise alongwith the environmental degradation. During the last few decades, reduction of GHG emissions and protection of the environment by using a green, efficient energy source that is able to replace the fossil fuels has become the center of attention. Indeed, the need of cutting down CO_2 emissions was seriously realized during early 1990s that resulted in the declaration of Kyoto Protocol. Although such international agreements have been signed by a majority of the nations (except some biggest fossil fuel consuming nations), greenhouse gas emissions are still expected to rise with serious inherent threats to sustainability of the biosphere. Global oil use surged by 3.4 percent in 2004, to 82.4 million barrels per day (Global Fossil Fuel Consumption Surges, 2014). In recent past, USA and China were the main fossil fuel consumers using almost half of the world's fossil fuels (Global Fossil Fuel Consumption Surges, 2014). The fossil fuel consumption of China was around 11% in 2004 which was ranked second in the world consuming 6.6 million barrels per day. In USA, the daily consumption was 20.5 million barrels a day — which was around 25% of the global fossil fuel usage. Geological experts have raised doubts in meeting such a huge global oil requirements in future and others projected that annual fuel production will fail to meet these demands as early as the middle of the next decade. It has been pointed out that oil output has considerably decreased during recently as compared to last three decades. Such decreased outputs in many oil producing countries suggest that the era of relatively stable oil prices is at an end (Global Fossil Fuel Consumption Surges, 2014).

The new renewable energy sources especially solar, wind and biomass is centre of attention at the moment (Popp, et al., 2014). In spite of their marginal contribution in total global renewable energy supplies, considerable research is being conducted to explore these energy sources. Prior to industrial revolution,

* Department of Environmental Sciences, COMSATS Institute of Information Technology, Abbottabad, Pakistan.
† Corresponding Author's Email: mahmoodzju@gmail.com

bioenergy was the main source of heat. Afterwards, the fossil fuels were the main energy source for various economic activities. The major objective of bioenergy development may be its use in the transportation sector in place of fossil fuels (Popp, et al., 2014).

2. BIOGAS

Biogas production may involve the use of various organic wastes particularly from food industry, sewage sludge, animal excreta or organic fraction of municipal wastes, etc. Various crops called as energy crops, especially maize, are being cultivated in certain countries which are digested to produce various forms of bioenergy (Boone, et, al., 1993; Mata-Alvarez, et al. 2000). The biomass production in many European countries is a common practice at the moment (de Graaf and Fendler, 2010). In Germany alone, maize is produced for its use in bioenergy production (Weiland, 2010).

There are several advantages of biogas which include; it is a mean to convert chemical energy contained in the waste to a beneficial usable form of energy, the digestate produced during this process can be employed in land farming to enhance crop productivity, and finally it is means to reduce solid waste and its hazardous environmental impacts (Zieminski and Frac, 2012). Bacterial consortium of anaerobic bacteria takes part in methanogenesis through degradation of organic substrates. The composition of waste materials used in the process usually determines the quality of produced biogas.

Methane CH_4 (50–75%); carbon dioxide CO_2 (25–45%); hydrogen sulfide H_2S (0–1%); hydrogen H_2 (0–1%); carbon monoxide CO (0–2%); nitrogen N_2 (0–2%); ammonia NH_3 (0–1%); oxygen O_2 (0–2%); and water H_2O (2–7%) (de Graaf and Fendler, 2010). The produced biogas has many commercial usages (Claassen, et al, 1999; Verstraete, et al, 2002), like in industry and power production:

i. Thermal energy for boilers is being produced along electric energy in associated units – (2.1 kWh of electrical energy and 2.9 kWh of heat is obtained from 1 m^3 of biogas);
ii. The electric energy in spark for igniting turbine engines;
iii. Fueling of transport vehicles; and
iv. Use in different technological units, e.g. in the production of methanol.

Arbon (2002) has reported the average efficiency of anaerobic systems to be around 0.24 m^3 of methane from 1 kg of dry organic matter. One cubic meter of biogas has calorific value of 26 MJ m^{-3} may replace 0.77 m^3 of natural gas with 33.5 MJ calorific value, 1.1 kg of hard coal with 23.4 MJ calorific value or 2 kg of firewood of 13.3 MJ calorific value (Arbon, 2002). Shah, et al. (2014) have comprehensively reviewed various aspects of microbial ecology of anaerobic digesters. In view of the limited supply of fossil fuels, biofuels have been considered as future fuels. Biofuels can be produced at a very low cost as compared to fossil fuels and are thus economical. Fossil fuels are produced naturally over a span of millions of years under high pressure and temperature in Earth, while biofuels can be produced in a short period, from a number of biomasses. Significantly less carbon output and fewer toxins are produced from burning of biofuels, making them a safer alternative to preserve atmospheric quality and lower air pollution. The poorly developed tropical countries can be benefitted from biogas technology due to its suitability of climatic conditions there, as optimum biogas production has been observed at temperatures around 30–35°C (Chakraborti and Guha, 1991).

Biogas is considered as clean form of energy, which has potential to replace fossil fuels and help reduce green house emissions. However, there are certain constrainsts for its full scale implementation and full utilization (Gupta, et al., 2012). Still its use has been advised due to a number of reasons which include: energy gain, off shooting the harmful impacts of suspended solids, alleviating the cost of waste treatment to almost half over aerobic systems, and the production of good quality effluent for irrigation and a compact treatment system (Kalogo and Verstraete, 1999). The technology results in mineralization of organic matter in the form of methane gas and CO_2 in discrete steps, by the rigorous activity of several microbial consortia (McInerney and Bryant, 1981). Initially, fermentative bacteria (FB) hydrolyze the polymers like polysaccharides, proteins and lipids, and ferment the hydrolysis products to acetate and longer chain fatty acids, CO_2, formate, H_2, NH_4^+ and HS^-. Further, a group of organisms, called proton-reducing acetogenic bacteria, degrade propionate and longer chain fatty acids, alcohols, amino acids and aromatic compounds to the methanogenic substrates, H_2, formate, and acetate. The degradation of these compounds with hydrogen production is thermodynamically unfavorable unless the concentration of H_2 or formate is kept low by H_2 utilizing bacteria as methanogens (McInerney and Bryant, 1981). Finally, two types of methanogenic bacteria i.e. the hydrogenotrophic methanogens that use hydrogen and formate produced by other bacteria to reduce CO_2 to CH_4 and the acetotrophic bacteria metabolize acetate to CO_2 and CH_4 (Figure-1).

3. TECHNOLOGICAL ASPECTS OF METHANOGENESIS

The chemical properties of various substrates can greatly influence the methanogenesis and ultimately the biogas concentration. Various nutritional requirements of the bacterial species involved in methanogenesis help them to grow and multiply in narrow range of conditions. The nutrients ratios especially those of carbon, nitrogen, phosphorus and sulfur (C:N:P:S) at 600:15:5:3 are best for the methanogens to grow (Weiland and Hassan, 2001). Methane production can be accomplished at a range of temperatures e.g. psychrophilic (<20°C) to thermophilic conditions (>60°C) (Kashyap, et al., 2003). Increasing the temperature may enhance the process through its effect on various enzymes involved in the process by increasing the solubility of organic compounds and increase death rates of pathogenic bacteria (Boe, 2006). However, an adequate nutrient supply must be ensured for the maximum microbial growth; major nutrients such as Carbon and Nitrogen (Kayhanian and Rich, 1995) and minor nutrients, such as Fe, Zn and Co (Cobalt) are important for proper microbial growth (Cresson, et al., 2006). Various authors have reported that best range of C/N ratio varies between 10 and 30, with an optimum between 15 and 25 (Speece, 1984; Nyns, 1986; Hansson and Christenssen, 2005; Yen and Brune, 2007; Liu, et al., 2008). This ratio has a noteworthy influence on fatty acid production and its production rates during methane generation (Liu, et al., 2008). It is often suggested that an optimum C/N ratio is between 20:1 and 30:1. The synthesis of bacterial enzymes involved in the waste degradation is hampered if nitrogen is not in adequate supply. However, increased nitrogen supply may cause the production of NH_3, thereby inhibiting bacterial activity. C/N ratio in range of 20-30 enhances the production of fatty acids (Callaghan, et al., 2002; Yen and Brune, 2007; Liu, et al., 2008). Likewise various bacterial species have varying pH requirements; while methanogens work in a very narrow pH range (from 5.5-7.5) (Boe, 2006). Fermentative bacteria work at pH range of 4.0-8.5. Volatile Faulty Acids (VFAs) are the intermediate compounds produced during anaerobic digestion. VFAs are subsequently transformed into methane and carbon dioxide (Pind, et

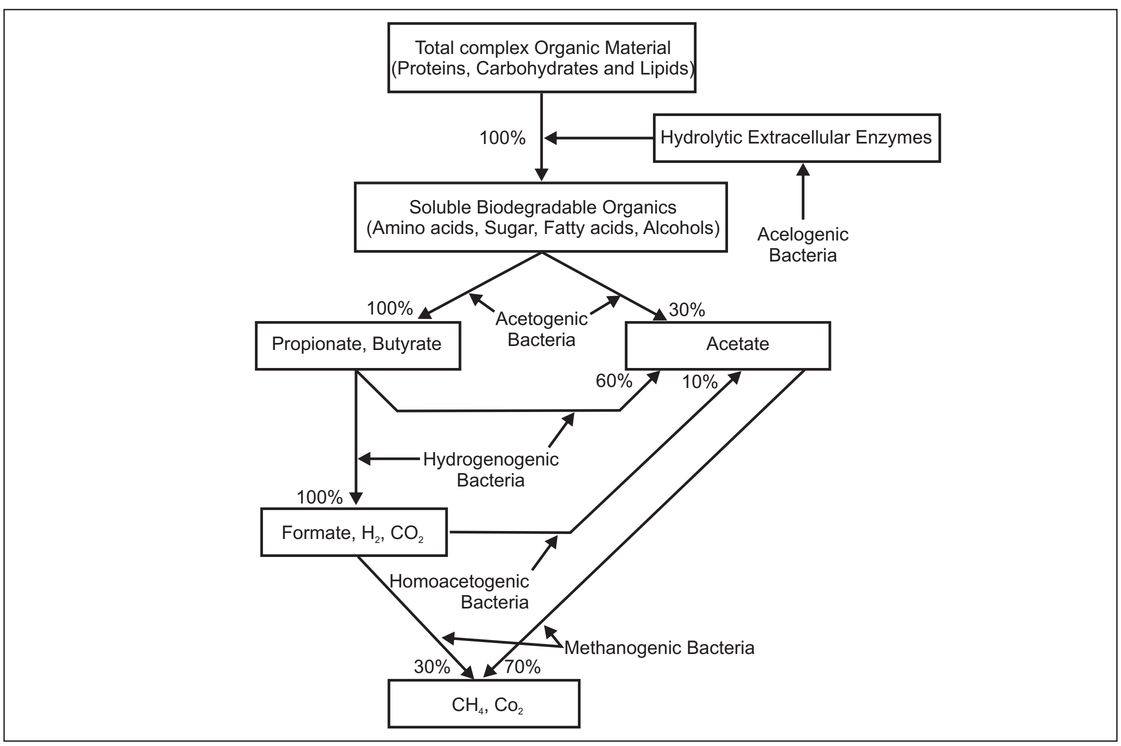

Figure-1: Schematic Diagram Showing the Various Steps Involved in the Complete Degradation of Organic Matter to Methane and Carbon Dioxide (McInerney and Bryant, 1981)

al., 2003). The VFAs concentration may increase during process disturbance and their increase leads to the process failure (Tiwari, et al., 2006).

The loading rate is defined as the concentration of organic substance fed into the digester on daily basis which is dependent upon the total capacity of the digester. Majority of wastes are biodegradable and produce high biogas yields; certain wastes can result in high VFA generation. Under-loading produces less amount of biogas, while overloading may lead to excessive VFA production which is another abnormality, so proper amount of loading is very crucial. Various harmful substances like antibiotics, heavy metals and detergents may cause process failures. The Table-1 shows the concentration (mg L^{-1}) for a variety of inhibitors.

Batch mode operation is better choice to determine the effect of retention time as compared to continuous mode. Agitation or mixing is normally helpful in bringing substrates in contact with the bacterial cell surface which then convert into products. Agitation also helps in removing produced biogas to be collected at the top of digester. It also minimizes the foam production in the reactor which may cause process disturbances. Various feed stocks employed and tested in the anaerobic process include:

- Waste from various foods both cooked and uncooked;
- Used oil and other fats;
- Most widely used material is animal wastes;
- Waste suldges from domestic and municipal sources.

Recently, the digestion of two types of waste substrates i.e. co-digestion is gaining popularity that increases the biodegradability and ultimately high biogas yields (Weiland, 1999; Kaparaju, et al., 2006).

4. BIOGAS POTENTIAL OF ALGAL BIOMASS

Methane production from microalgal biomass has been investigated for many freshwater and marine microalgae. The digestibility of microalgal biomass significantly varies even between closely related species (Mussugnug, et al., 2010). CH_4 yields from microalgae vary depending upon their biochemical composition, cell wall structure and other process parameters like bioreactor type and the operational temperature. Theoretically, proteins, carbohydrates and lipids yield 0.851, 0.415 and 1.014 L CH_4 per gram of volatile solids, respectively (Sialve, et al., 2009). Chemical composition of microalgal biomass varies among microalgal species and even within the same species under different growth conditions (Sheehan, et al., 1998). Biogas potential of various microalgal species should be investigated in future studies.

Rigid eukaryotic cell walls of microalgae can limit the anaerobic digestion of the biomass (Golueke, 1957; Chen and Oswald, 1998). Biogas generation often depends on the temperature of the digester. Due to chemical composition of the microalgae, some pretreatment is required to enhance biogas production from such feed stocks. For example, Golueke et al. (1957) reported 5–10% increase in digestibility of microalgal biomass, when the digestion temperature was increased from 35 to 50°C. Chen and Oswald (1998) increased the CH_4 yield by 33% by heat pretreating microalgal biomass at 100°C for 8 hours. In both examples, the amount of energy spent during pretreatment was higher than the amount recovered from the process (Sialve, et al., 2009; Yen and Brune, 2007). Drying of microalgal biomass prior to digestion would also increase energy consumption and has been reported to reduce CH_4 yields (Mussugnug et al., 2010). These findings together with data on terrestrial plant materials (Lakaniemi, et al., 2012) indicate that pretreatments of microalgal biomass do not increase the energy gain of CH_4 production. Biomass slurries of salt water algae contain sodium, calcium and

Table-1: Limiting Concentration for Various Inhibitors for Biogas Generation

Substance	Symbol	[mg/L]
Copper	Cu	10-250
Calcium	Ca	8000
Sodium	Na	8000
Magnesium	Mg	3000
Nickel	Ni	100-1000
Zinc	Zn	350-1000
Chromium	Cr	200-2000
Sulphide (as sulphur)	S	200
Cyanide	CN	2

magnesium ions that are inhibitory to anaerobic digestion at high concentrations. Methanogens are sensitive to excessively high salinity levels but their susceptibility varies. Lakaniemi, et al. (2011) reported significantly lower CH_4 yields from NaOH-flocculated marine microalga Dunaliella tertiolecta than from chitosan-flocculated freshwater microalga Chlorella vulgaris. Mussgnug, et al. (2010) reported similar or higher CH_4 production from marine microalga, D. salina, than from freshwater species. Factors affecting the level of inhibition of methanogenesis include: biomass feedstock type and concentration and source and previous growth history of microbial consortia in anaerobic digestion. Potential salt inhibition can be reduced by using cultures from saline environments and by successive enrichment at incremental concentrations of salt ions (Feijoo, et al., 1995).

Due to presence of high protein content in algal biomass under optimal growth conditions, the biomass has a relatively low C/N ratio, which may reduce digestibility and cause ammonium accumulation (Yen and Brune, 2007). C/N ratio can be adjusted to more optimal values with C-rich co-substrates, such as cellulose (e.g., waste paper) (Yen and Brune, 2007) or glycerol (Ehimen, et al., 2009). The C/N ratios of algal biomass can also be modified by selecting growth conditions that reduce cellular protein synthesis and favor lipid or carbohydrate production; an example is nitrogen limitation (Sheehan et al., 1998). High lipid content would increase the theoretical CH_4 yield, whilst it can also cause problems in the digestion due to adhesion of fat on cell surfaces. This may lead to mass transfer limitations and unwanted floatation of digester biomass. Nitrogen limited cultivation would be useful for energetic balance and sustainability of microalgal biomass production because nitrogen fertilizer production consumes significant amount of energy (Ras, et al., 2011). When normalized to surface area, microalgal biomass production requires substantially more nitrogen as compared to most terrestrial plants (Sialve, et al., 2009).

The anaerobic digestion of untreated biomass usually takes longer retention times to get high biogas yields i.e. 20–30 days (Hulatt, et al. 2012; Zamalloa, et al., 2011). Anaerobic digestion of microalgal biomass has been investigated in batch and fed-batch systems, as well as in continuously stirred tank reactors (Sialve, et al., 2009). Zamalloa, et al. (2011) suggested that anaerobic sludge blanket reactors, anaerobic filter reactors and anaerobic membrane bioreactors should be tested due to their high volumetric conversion rates. These processes have been designed for wastewater treatment and high solid contents of micro algal slurry may interfere with generation of anaerobic biomass and clog the membranes. It was suggested by Verstraete, et al. (2011) that effective biomethane rate can be obtained from algae at the loading rate of 20 kg DM m^{-3} day^{-1}. Mussugnug, et al. (2010) demonstrated that biogas potential is strongly dependent on type of species and pretreatment. Fermentation of green algae Chlamydomonas reeinhardtii was efficient with the production of 587 mL biogas per gV S^{-1}. However, the fermentation of Senedesmus obliquus was inefficient, with only 287 mL biogas per gV S^{-1} being produced (Mussugnug, et al., 2010). The methane content was significantly increased due to addition of carbon-rich corn straw to the co-digestion process with Taihu blue green algae (Zhong, et al., 2012). The C/N ratio of 20:1 was found to be the best in terms of methane productivity, which is increased by 61.69% as compared to algae digestion alone. The co-digestion of macroalgae (15%) with WAS (85%) is feasible at a rate of methane production 26% higher than WAS alone without decreasing the overall biodegradability of the substrate (42–45% methane yield) (Zhong, et al., 2012).

The methanogenesis of microalgae should be accomplished at Substrate/Inoculum (S/I) ratio of 0.5 to avoid process imbalance caused by VFA accumulation. TSS concentrations of 10 g TS/kg are required to obtain the highest biodegradability and biogas production. The results obtained confirm that the Bio Methane Potential (BMP) depended on the microalgal species. Likewise, the NH_4^+ released was independent of the biomass concentration and the S/I ratio used. Thermal hydrolysis was the most effective pretreatment, supporting the increase of productivity and biodegradability to over 60%. The required temperature during pretreatment depended on the amount of substrate (Costa, et al., 2012; Alzate, et al., 2012).

5. BIOGAS IN DEVELOPING COUNTRIES

Biogas is one of the renewable technologies; its 60% constitutes methane which can be employed in household or commercial energy consuming processes.

Anaerobic technology has been widely used in many developing countries especially in India and China with 4 and 27 million biogas plants, respectively (Bond and Templeton, 2011). Traditionally, the anaerobic digesters were run by feeding livestock wastes, Process failures in many countries could be explained on the basis of lack of skilled personals to operate the biogas plants. There is need to establish biogas recovery technology and operational support networks in future. Currently, it has been realized that new substrates such as kitchen waste, weeds and crop residues should be tested for their potential of biogas production. Further, there is need to enhance the biodegradability of such substrates for better biogas yields (Bond and Templeton, 2011). Low population densities in many rural African communities may depend on the low cost biogas technology to avoid their dependence on costly fossil fuels. Biogas plant serves the dual purposes of reducing environmental pollution and generating energy (Amigun and von Blottnitz, 2010).

A number of environmental concerns have been posed by the concentrated effluents from palm oil mill effluent (POME) in Malaysia. Such effluents have very high organic contents which are best suited for the biogas digesters to generate biogas. Biogas generated from anaerobic digestion of POME can replace palm kernel shell and mesocarp fiber, which has higher economic value as boiler fuel; upgraded to be used in gas engine for power generation. It is estimated that net profit of RM 3.8 million per year can be obtained in a palm oil mill with processing capacity of 60 tones/hr from electricity generation using biogas produced from POME treatment (Ji, et al., 2013).

On one hand, the main factors identified as positively promoting the adoption of biogas technology are education, number of cattle, family income, family size and age. On the other hand, the main factors negatively correlated with the household's decision to adopt biogas technology are gender, and number of poultry birds. Education plays a very important role in the biogas plants adoption process, as the more the family-head is educated, the more this household is likely to adopt biogas technology. The number of cattle belonging to the household is another core component of producing biogas. Female headed households have more interest in taking the decision to use biogas plants. Regarding the initial investments required, income is also a determining factor in the adoption process of biogas technology within the household.

United Nations is committed to promoting sustainable renewable energy by adopting new arrangement on subsidies, taxes, and some other policies. The existing subsidy and flat credit system can be continued for a standard level where visible incentives are offered by government. Moreover the benefits of renewable energy as well as biogas technology need to be highly publicised especially to rural populations. Thus, electronic and print media could help to spread the technology throughout the country. Local governments and elites could also support the expanding of the biogas technology. They could draw the public attention on the existing energy problem, which could be solved by adopting the biogas technology.

Despite its huge potential and numerous advantages, significant role of renewable energy still lags behind the ambitious claims for it due to the initially high investment costs, concerns about local impacts, lack of research outcomes and poor institutional and economic arrangements (Duchin, 1995). However, local awareness of the benefits of biogas and willingness to adapt combined with availability of subsidies, as well as soft loan to enable the installation of the biogas plant, stand out for the most important factors contributing to a successful large-scale uptake of the technology.

Biomass supplies more than 11.5% of the world's primary energy and about 79.7% of the world's energy consumption (Maghanaki, et al., 2013). In 2012, about 194.8 million ton of renewable energy was consumed in the world and about 0.1 million ton was consumed in Iran. Biogas was produced by anaerobic fermentation. Global biogas capacity would reach 22,000 Mega Watt (MW) by 2025. European biogas electricity production in 2006 was 17,272 GWh per year, of which 7338 Giga Watt Hour (GWh) was by Germany alone. Biogas now represents 1.2% of the annual production of electricity and nearly 10% of renewable energy, with an installed power close to 1500 MW. A published analysis by Global Information Inc (GII) showed, global biogas installed capacity is expected to achieve moderate growth over the next 12 years, reaching 22.040 MW by 2025 and making a Compound Annual Growth Rate (CAGR) of 7.2%. The world biogas market has grown considerably between 2001 and 2011, with installed capacity expanding to 8.377 MW in 2011 from 2.388 MW in 2001. This equals a CAGR of 13.4%. The potential of biomass sources in Iran is estimated to be 132 million ton (oil equivalent) in the form of agricultural and forest wastes, livestock wastes, municipal wastes, sewage and industrial wastes. Biogas in Iran would generate about 16,146.35 million m^3, which is approximately 323 petajoule of energy. The potential of biogas production from biomass sources in Iran presents examples of biogas production, applications and quantitative potential of different sources in the country (Maghanaki, et al., 2013).

Biogas is becoming an increasingly important source of clean energy for rural and urban areas in developing countries, as can be seen by the increased construction of biodigesters. Biogas digester technology has been domesticated in Nigeria and a number of pilot biogas plants have been built with majority (over 75%) of operational Nigerian manure digesters on piggery, cattle farms or abattoirs. A trend is now seen among academic institutions in Nigeria in the design and construction of biogas digesters. These technologies include biogas digesters that are being used to collect farm animal waste, which is converted into biogas through anaerobic processes (Temilola, et al., 2014).

6. DESIGN OF ANAEROBIC DIGESTERS

For an optimum biogas yield, various process parameters like higher organic loading rate (OLR), and low hydraulic retention time (HRT) are crucial (Ward, et al., 2008). Operational parameters, e.g. HRT, mixing, number of tanks, process temperature (Vandevivere, et al., 2003) and the properties of the feedstock may serve as the basis of digester design (Lynd, et al., 2002). It was suggested that the digestion of lignocellulosic substrates, such as grass silage, the dry matter content, and the solubility and hydrolysis rates played a critical role (Qi, et al., 2005). The information given in Table-2 compared the efficiencies of various kinds of digester configurations as presented by various researchers (Marchaim, 1992; Barnett, 1978; Vandevivere et al., 2003; Lehtomäki, et al., 2004). The strengths and weaknesses of various digesters have been presented in Table-3.

In one-stage digestion involves all the microbiological phases in one tank to accomplish anaerobic digestion (Callander and Barford, 1983). While two-stage process involves two microbial phases separated from each other (Vandevivere, et al., 2003). Two-stage digestion may allow both stages to be complete microbial processes with the second stage incorporating storage of digestate and remedial gas collection (Yu, et al., 2002). Normally hydrolysis and and rest of stages are performed in two separate digesters (Gunaseelan, 1997). Two stage processes have potentially higher biogas yields in smaller digesters (Liu, et al., 2006). The pilot and lab-scale two-stage systems for anaerobic digestion of Municipal Solid Waste (MSW), agricultural residues and market waste were studied by Parawira et al. (2008). Majority of the investigators, used two-stage digesters for lab-scale or pilot scale studies but didn't use them for commercial biogas generation. In the one-stage process may involve either dry batch systems or wet continuous systems. Whereas, continuous and wet processes are preferred in the two-stage process (De Baere, 2008).

Vandevivere, et al. (2003) named digesters with the feedstock comprising of 20–40% dry matter as dry anaerobic digesters. While those with less than 20% dry matter were classified as wet digesters. Currently, one-stage dry continuous and dry batch digesters are relatively new. The use of innovative digesters for Municipal Solid Waste (MSW), biowaste and grass silage is expected to continue in the future. One-stage dry batch systems typically employ a system whereby high solid content feedstock is fed into a vessel without initial dilution. Recirculation of water/leachate is employed. No mixing is required and its parasitic energy demands are very low (Vandevivere, et al., 2003). Vertical continuously stirred tank reactor (CSTR) configuration is the most commonly used configuration in 90% of the newly erected wet digesters (Weiland, 2006).

The feeding of batch mode digesters is usually simple; they are fed, sealed and placed for certain time period (Barnett, 1978). In contrast, the substrate is regularly and continuously fed either mechanically or by force of the newly entered substrate in continuous digesters, (Demirbas and Ozturk, 2005). Plug flow, CSTR, anaerobic filters and upflow anaerobic sludge blanket (UASB) systems are the examples of the continuous systems. About 90% of the industrial scale plants currently operating in Europe are different 'continuous type' digesters in configurations (Bouallagni, et al., 2005), e.g., a continuous one-stage digester (Lissens, et al., 2001) used for anaerobic digestion of OFMSW, solid waste and biowaste. However, batch digesters may be more suitable for grass silage digestion due to the dry solid contents (bailed silage has solids content of about 32%) (Lettinga, 1995).

High solid retention time is achieved through attachment of biomass to high density carriers and formation of highly settleable granules in anaerobic reactors (Lettinga, 1995). Upflow anaerobic filters, UASB, anaerobic packed-bed and fluidized bed reactors are utilized as high-rate digesters for both lab and industrial scales. The use of UASB among high-rate digesters has increased and widened recently (Weiland, 2003) by taking feed with solid content less than 4% or up to 15% (Barnett, 1978; Barampouti, et al., 2005) at retention times of 0.5–12 days (Vandevivere, et al. 2003). Marchaim (1992) suggested solid content of less than 4% in UASB,

Table-2: The comparison of different digester configurations for high solid content feed stocks

	One-stage versus two-stage digesters		Dry versus wet digesters		Batch versus continuous digesters		High-rate bioreactors
	One-stage	Two-stage	Dry	Wet	Batch	Continuous	
Biogas production	Irregular & dis-continuous	Higher and stable	Higher	Less and irregular	Irregular and dis-continuous	Continuous	Continuous and higher
Solid content	10-40%	2-40%	20-50%	2-12%	25-40%	2-15%	<4-15%
Cost	Less	More	Less	More	Less	More	More
Volatile solids destruction	Low to high	High	40-70%	40-75%	40-70%	40-75%	75-98%
HRT (days)	10-60	10-15	14-60	25-60	30-60	30-60	0.5-12
OLR (kg VS m^{-3} d^{-1})	0.7-15	10-15 for second stage	12-15	<5	12-15	0.7-1.4	10-15

Source: *Marchaim, 1992; Barnett, 1978; Vandevivere, et al., 2003; Lehtomäki, et al., 2004*

while Barnett, et al. (1978) allowed for solid content of up to 15% in UASB. Moreover, the UASB reactor is suggested by various authors (Bal and Dhagat, 2001; Paula and Foresti, 1992) to offer benefits over other high-rate digesters, when applied to high organic loading rates. For digestion of grass silage, high-rate digesters are applied in connection with leach beds (Lehtoma¨ki, et al., 2008; Yu, et al., 2002).

Low-cost tubular digesters originally developed in tropical regions adapted to the extreme weather conditions for production in household digesters located at high altitude, operating under psychrophilic conditions. The useful volume of the digester ranged between 2.4 and 7.5 m^3, and hydraulic residence time (HRT) between 60 and 90 days. The temperature inside the digester's greenhouse ranged between 20 and 25°C. A specific biogas production around 0.35 m^3/kg was obtained while treating cow manure, with some 65% CH_4 in biogas (Ferrer, et al., 2011). The solar radiation, wind velocity, ambient temperature and digester geometry, known as time dependent thermal model, affect the performance of tubular digester. The model outputs include temperature of the slurry, the biogas, its holding membrane and the green house air, wall and cover. Heat transfer phenomena through radiation, convection and conduction are considered between all systems elements (Perrigault, et al., 2012). At high altitude the unheated tubular co-digester is implemented to investigate the biogas productions and green house effect on process temperature. The result shows that biogas productions through the co-digestion (0.08 m^3 biogas m^{-3} digester d^{-1}) outweigh guinea pig manure digestion, (0.03 m^3 biogas m^{-3} digester d^{-1}), but did not improve cow manure digestion (0.12 m^3 biogas m^{-3} digester d^{-1}), which may be due to characteristics of guinea pig manure. The effect of temperature of the green house is doubtful because the internal temperature of liquor is fairly constant (20°C) (Garffi, et al., 2011).

In tubular digester the methane yields from the co-digestion of olive mill waste water with olive mill solid waste (TCOD=56 g COD/L) at an HRT of 12 days is 0.95 l/l/d. However, it is 0.7 l/l/d when olive mill waste water is digested alone at the same conditions of HRT and TCOD (Boubaker and Ridha, 2006). Increase in methane production is quantified when swine manure was co-digested with used cooking grease in plug flow digesters that operate at ambient temperature without mixing. When 2.5% cooking grease is co-digested with swine manure produced high amount of methane 45 l/day, a 1245 increase from the control, with a total biogas productions of 67.3 L/day and 66.9% CH_4 in the produced biogas. Adding small amounts of grease to the influent is a simple way to double energy production without affecting other digester benefits. Due to difference in digester green house design the dome roof digester the biogas production is higher than in shed roof digester. However, due to low organic loading rate (0.6 kg VS m^3 digester d^{-1}) and temperature the biogas production is low (Garffi, et al., 2011).There are two problems associated with low

Table-3: The strengths and weaknesses of various digester configurations

System		Strengths	Weaknesses
One-stage versus two-stage digesters	One-stage	Simpler design	Higher retention time
		Less technical failure	Foam and scum formation
		Low cost	
	Two-stage	Efficient substrate degradation owing to recirculation of digestate	Complex and expensive to build and maintain
		Constant feeding rate to second stage	Solid particles need to be removed from second stage
		More robust process	
		Less susceptible to failure	
Dry versus wet digesters	Dry	Higher biomass retention	Complex handling of feedstock
		Controlled feeding	Mostly structured substrates are used
		Simpler pretreatment	Material handling and mixing is difficult
		Lower parasitic energy demands	
	Wet	Good operating history	Scum formation
		Degree of process control is higher	High consumption of water and energy
			Short-circuiting
			Sensitive to shock loads
Batch versus continuous digesters	Batch	No mixing, stirring or pumping	Channeling and clogging
		Low input process and mechanical needs	Larger volume
		Cost-effective	Lower biogas yield
	Continuous	Simplicity in design and operation	Rapid acidification
		Low capital costs	Larger VFA (Volatile Fatty Acid) production
High-rate bioreactors		Higher biomass retention	Larger start-up times
		Controlled feeding	Channeling at low feeding rates
		Lower investment cost	
		No support material is needed	

Source: *Marchaim, 1992; Barnett, 1978; Vandevivere, et al., 2003*

cost tubular digester, i.e hydraulic retention time and biogas pressure. The hydraulic retention time is normally determined from the liquid volume calculated from the cylindrical shape of the bag and not from the trench dimensions. This causes the reduction in HRT from 6% to 51% depending on the dimensions of the trench. While the biogas pressure reducing HRT by as much as 15% (Marti-Herrero, 2011).

7. CONCLUSIONS

Biogas has considerable potential to replace fossil fuels and it is considered as clean technology with smaller green house gas emissions. In view of limited supply of fossil fuels, biofuels have been considered as future fuels. Biofuels can be produced at a substantially low cost as compared to fossil fuels and are thus economical. Lack of awareness renders the under utilization of the potential of this option. Anaerobic digestion employs various types of feed stocks mainly organic in nature arising from food industry and municipal sources. The cultivation of energy crops is the main focus currently to replace fossil fuels with renewable bioenergies in many countries. Codigestion of various feed stocks has been thought to be better choice over monodigestion. The chemical composition of feed substrates is crucial in determination of biogas produced. In view of high polymeric substrates in feed stock, pretreatment has been suggested to increase biogas production. Two-stage process usually produces greater biogas and it needs to be employed at full scale. Agitation of substrate is another option to enhance the biogas production.

REFERENCES

- Alzate, M.E., Munoz, R., Rogalla, F., et al., 2012. Biochemical methane potential of microalgae: Influence of substrate to inoculum ratio, biomass concentration and pretreatment. *Bioresource Technology,*123, pp.488-494.
- Amigun, B., and Blotz, H. von, 2010. Capacity-cost and location-cost analyses for biogas plants in Africa. *Resources, Conservation and Recycling,* 55, pp. 63-73.
- Arbon, I., 2002. Worldwide use of biomass in power generation and combined heat and power schemes. Proceedings of the Institution of Mechanical Engineers, *Part A. Journal of Power Energy*, 216(1), pp. 41-57.
- Bal, A.S., and Dhagat, N.N., 2001. Upflow anaerobic sludge blanket. A review. *Indian Journal of Environmental Health*,43(2), pp. 1-82.
- Barampouti, E.M.P., Mai., S.T, and Vlyssides, A.G., 2005. Dynamic modeling of biogas production in an UASB reactor for potato processing wastewater treatment. *Chemical Engineering Journal*,106, pp. 53-58.
- Barnett, A., Pyle, L., and Subramanian S.K., 1978. Biogas technology in the third world. A multi-disciplinary review. Ottawa: IDRC Publications.
- Boe, K., 2006. Online Monitoring and Control of the Biogas Process. Doctoral thesis, Institute of Environment & Resources, Technical University of Denmark, ISBN 87-91855-10-11.
- Bond, T., and Templeton M.R., 2011. History and future of domestic biogas plants in the developing world. *Energy for Sustainable Development,* 15, pp. 347-354.
- Boone, D. R., et al., 1993. Ecology and microbiology of biogasification. *Biomass Bioenergy,* 5(3), pp. 191-202.
- Bouallagni, H., et al., 2005. Bioreactor performance in anaerobic digestion of fruit and vegetable wastes. *Process Biochemistry,* 40, pp. 989-95.
- Boubaker, F., and Ridha, B.C., 2006. Anaerobic co-digestion of olive mill wastewater with olive mill solid waste in a tubular digester at mesophilic temperature. *Bioresource Technology*, 98, pp. 769-774.
- Callaghan, F.J., Wase, D.A.J., Thayanithy, K., and Forster, C.F., 2002. Continuous Co-digestion of Cattle Slurry with Fruit and Vegetable *Wastes and Chicken Manure. Biomass and Bioenergy.* 22, pp. 71-77.
- Callander, I.J., and Barford J.P., 1983. Recent advances in anaerobic digestion technology. *Process Biochemistry,* pp. 24-30.
- Chakraborti, R.K., and Guha, D., 1991. Biogas, An overview and the role of enzyme extract and anchored enzymes in enhanced and methane-enriched biogas generation. *Research and Industry,* 36, pp. 114-23.
- Chen, P.H, and Oswald, W.J., 1998. Thermochemical treatment for algal fermentation. *Environment International,* 24, pp. 889-897.
- Claassen, P., et al., 1999. Utilisation of biomass for the supply of energy carriers. *Applied Microbiology Biotechnology*.52(6), pp. 741-755.
- Costa, J.C., Goncalves, P.R., Nobre, A., and Alves, A.A., 2012. Biomethanation potential of macroalgae Ulva spp. and Gracilaria spp. and in co-digestion with waste activated sludge. *Bioresource Technology*,114, pp. 320-326.
- Cresson, R., Carrère, H., Delgenès, J.P., and Bernet, N., 2006. Biofilm Formation During the 5 Start-up Period of an Anaerobic Biofilm Reactor-Impact of Nutrient Complementation. *Journal Biochemical Engineering,* 30, pp. 55-62.
- De Baere, L.D., and Mattheeuws, B., 2008. Anaerobic digestion of solid waste. Waste Management World. [Online]. Available at: <http://www.waste-management-world.com/articles/print/volume-9/issue-4/features/state-of-the-art-2008-anaerobic-digestion-of-solid-waste.html>.
- de Graaf, D., and Fendler, R., 2010. Biogas production in Germany. SPIN Background Paper: 2010; pp. 24.
- Demirbas, A., and Ozturk, T., 2005. Anaerobic digestion of agricultural solid residues. *International Journal of Green Energy,* 4, pp. 483-94.
- Duchin, F., 1995. Global scenarios about lifestyle and technology, the sustainable future of the global system. Tokyo: United Nations University.

- Ehimen, E.A., Connaughton, S., Sun, Z., and Carrington, G.C., 2009. Energy recovery from lipid extracted, transesterified and glycerol codigested microalgae biomass. *Global Change Biology Bioenergineering.* 1 pp. 371-381.
- FAO, 2011. World Livestock - livestock in food security. Rome.
- Feijoo, G., Soto, M., Mendez, R., and Lema, J.M., 1995. Sodium inhibition in the anaerobic digestion process. Antagonism and adaptation phenomena. *Enzyme and Microbial Technology,* 17 pp. 180-188.
- Ferrer, I., et al., 2011. Biogas production in low-cost household digesters at the Peruvian Andes. *Journal of Biomass Bioenergineering,* 35, pp. 1668-1674.
- Garffi, M., Ferrer-Marti, L., Villegas, V., and Ferrer, L., 2011. Psychrophilic anaerobic digestion of guinea pig manure in low-cost tubular digesters at high altitude. *Bioresource Technology,* 102, pp. 6356-6359.
- Global Fossil Fuel Consumption Surges, 2014. Available at: <http://www.worldwatch.org/global-fossil- fuel-consumption-surges> Accessed on April 2, 2014.
- Golueke, C.G., 1957. Comparative studies of the physiology of Sapromyces and related genera. *J Bacteriol,* 74, pp. 337-343.
- Gunaseelan, V.N., 1997. Anaerobic digestion of biomass for methane production: a review. *Biomass Bioenergineering,* 13, pp. 83-114.
- Gupta, P., et al., 2012. A re-appraisal on intensification of biogas production. *Renewable and Sustainable Energy Reviews,* 16, pp. 4908-4916.
- Hansson, A., and Christensson, K., 2005. Biogas Energies and Organic Farming. Report, in Swedish, Swedish Board of Agriculture (Jordbruksverket), Jönköping, Sweden.
- Hulatt, C.J., Lakaniemi, A.M., Puhakka, J. A., and Thomas, D. N., 2012. Energy Demands of Nitrogen Supply in Mass Cultivation of Two Commercially Important Microalgal Species, Chlorella vulgaris and Dunaliella tertiolecta. *BioEnergy Research,* 5, pp. 669-684.
- IEA Bioenergy, 2009. A sustainable and reliable energy source. Main Report. Paris. International Energy Agency.
- Ji, C.M., et al., 2013. Biogas from palm oil mill effluent (POME): Opportunities and challenges from Malaysia's perspective. *Renewable and Sustainable Energy Reviews* 26, pp. 717-726.
- Kalogo, Y., and Verstraete W., 1999. Development of anaerobic sludge bed (ASB) reactor technologies for domestic wastewater treatment: motives and perspectives. *Journal of Microbial Biotechnology,* 15, pp. 523-534.
- Kaparaju, N.L.P. and Rintala, J.A., 2006. Thermophilic Anaerobic Digestion of Industrial Orange Waste. Environmenta. Technology. 27, pp. 623-633.
- Kashyap, D.R., Dadhich, K.S. and Sharma, S.K., 2003. Biomethanation under Psychrophilic Conditions. a review. *Bioresource Technology*. 87, pp. 147-153.
- Kayhanian, M., and Rich, D., 1995. Pilot Scale High Solids Thermophilic Anaerobic Digestion of Municipal Solid Waste with an Emphasis on Nutrient Requirements. *Biomass and Bioenergy.* 8, pp. 433-444.
- Lakaniemi, A. M., et al., 2011. Biogenic hydrogen and methane production from Chlorella vulgaris and Dunaliella tertiolecta biomass. *Biotechnology for Biofuels,* 4, pp. 34-46.
- Lakaniemi, A. M., Intihar, V. M., Tuovinen O.H., and Puhakka, J. A., 2012. Growth of Chlorella vulgaris and associated bacteria in photobioreactors. *Microbial Biotechnology,* 5, pp. 69-78.
- Lehtoma, ki A., Huttunen, S., Lehtinen., T. M, and Rintala J. A., 2008. Anaerobic digestion of grass silage in batch leach bed processes for methane production. *Bioresource Technology,* 99, pp. 3267-78.
- Lehtomäki, A., et al., 2004. Effect of pre-treatments on methane production potential of energy crops and crop residues. In: Guiot SG, Pavlostathis S G, Lier JB. van (eds), Proc. the 10th World IWA Congress on Anaerobic Digestion: 1016-1021. IWA Publishing, London.
- Lettinga, G., 1995. Anaerobic digestion and wastewater treatment systems. *Antonie van Leeuwenhoek*. 67, pp. 3-28.
- Lissens, G., et al., 2001. Solid waste digesters: process performance and practice for municipal solid waste digestion. *Water Science and Technology* 44, pp. 91-102.
- Liu, C., et al., 2008. Prediction of Methane Yield at Optimum pH for Anaerobic Digestion of Organic Fraction of Municipal Solid Waste. *Bioresource. Technology*, 99, pp. 882-888.
- Liu, G. T., Peng, X. Y., and Long., T. R., 2006. Advance in high-solid anaerobic digestion of organic fraction of municipal solid waste. *Journal of Central South University of Technology,* 13, pp. 151-7.
- Lynd, L. R, Weimer, P.J, Zyl, W.H, and Pretorius, I. S., 2002. Microbial cellulose utilization:

fundamentals and biotechnology. *Microbiology and Molecular Biology Reviews,* 66, pp. 506-77.

- Maghanaki, M. M., Ghobadia, B., Najafi G., and Galogah, J., 2013. Potential of biogas production in Iran. *Renewable and Sustainable Energy Reviews* 28, pp. 702-714.
- Marchaim, U., 1992. Biogas processes for sustainable development. Rome: FAO Agricultural Services Bulletin.
- Marti-Herrero, J., 2011. Reduced hydraulic retention times in low-cost tubular digesters. Two issues. *Journal of Biomass Bioenergineering,* 35, pp. 4481-4484.
- Mata-Alvarez, J., Mace, S., Llabres, P., 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology* 74, pp. 3-16.
- McInerney, M. J., and Bryant, M.P., 1981. Review of methane fermentation fundamentals. In Wise, D.L., editor, *Fuel gas production from biomass*, CRC Press, pp. 19-46.
- Mussgnug, J. H., Klassen, V., Schlüter, A., and Kruse, O., 2010. Microalgae as substrates for fermentative biogas production in a combined biorefinery system. *Journal of Biotechnology,* 150, pp. 51-56.
- Nyns, E.J., 1986. Biomethanation Processes. In: Schonborn W. (ed), *Microbial Degradations.* 18, pp. 207-267.
- Parawira, W., Read, J. S., Mattiasson, B., and Bjornsson, L., 2008. Energy production from agricultural residues: high methane yields in pilot-scale two-stage anaerobic digestion. *Biomass Bioenergineering* 32, pp. 44-50.
- Paula, J. D. R., and Foresti E., 1992. Kinetic studies on a UASB reactor subjected to increasing COD concentration. *Water Science and Technology,* 25, pp. 103-11.
- Perrigault, T., Weatherford, V., Marti-Herroro, J., and Poggio, D. 2012. Towards thermal design optimization of tubular digesters in cold climates: A heat transfer model. *Bioresource Technology,*124, pp. 259-268.
- Pind, P.F., Angelidaki, I., and Ahring, B.K., 2003. A New VFA Sensor Technique for Anaerobic Reactor Systems. *Biotechnology and Bioengineering,* 82 1, pp. 54-61.
- Popp J., Lakner, Z., Harangi-Rákos, M., and Fári, M., 2014. The effect of bioenergy expansion: Food, energy, and environment: *Renewable and Sustainable Energy Reviews* 32, pp. 559-578.
- Qi, B. C., Aldrich, C., Lorenzen, L., and Wolfaardt G. W., 2005. Acidogenic fermentation of lignocellulosic substrate with activated sludge. *Chemical Engineering Communications,* 192, pp1221-42.
- Ras, M., et al., 2011. Experimental study on a coupled process of production and anaerobic digestion of Chlorella vulgaris. *Bioresource Technology,* 102, pp. 200-206.
- Shah, F.A., et al., 2014. Microbial Ecology of Anaerobic Digesters: The Key Players of Anaerobiosis, *The Scientific World Journal,* 21 pages.
- Sheehan, J., Dunahay, T., Benemann, J., and Roessler P., 1998. A Look Back at the U.S. Department of Energy's Aquatic Species Program - Biodiesel from Algae. *National Renewable Energy Laboratory,* Golden, CO.
- Sialve, B., Bernet, N., and Bernard, O., 2009. Anaerobic digestion of microalgae as a necessary step to make microalgal biodiesel sustainable. *Biotechnology Advances,* 27, pp. 409-416.
- Speece, R.E., 1984. Nutrient Requirements. Anaerobic Digestion of Biomass (Chynoweth, D.P. och Isaacson, R. (eds). Elsivier Applied Science, London. S, pp. 109-128.
- Temilola, T., Olugasa., O. F., and Oyewola, M.O., 2014. Energy production from biogas: A conceptual review for use in Nigeria. *Renewable and Sustainable Energy Reviews,* 32, pp. 770-776.
- Tiwari, M. K., Guha, S., Harendranath, C.S., and Tripathi, S., 2006. Influence of Extrinsic Factors on Granulation in UASB reactor. *Appllied Microbiology Biotechnology.* 71 pp. 145-154.
- Vandevivere, P., De Baere, L., and Verstraete, W., 2003. Types of anaerobic digester for solidwastes. In: Mata-Alvarez J, editor. Biomethanization of the organic fraction of municipal solid wastes. London: IWA Press. pp. 112-40.
- Verstraete, et al., 2002. The importance of anaerobic digestion for global environmental development. In: Proceedings-Japan Society of Civil Engineers, 2002. Dotoku gakkai, p 97-102.
- Verstraete, W., Zalmallo, C., Vulsteke, E., and Albrecht, J., 2011. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource Technology,*102 pp.1149-1158.
- Ward, A. J., Hobbs, P. J, Holliman, P J., and Jones, D.L., 2008. Optimization of the anaerobic digestion of agricultural resources, review. *Bioresource Technology,* 99, pp. 7928-40.
- Weiland, P., 1999. Co-digestion - processes, potentials and organization forms. V: ORBIT 99

Organic Recovery & Biological Treatment. Bidlingmaier W., de Bertoldi M., Diaz L.F. and Papadimitriou E.K. (eds.): Berlin. 179-187.

- Weiland, P., and Hassan, E., 2001. Production of Biogas from Forage Beet. Processing of ninth world congress, anaerobic conversion for sustainability, 2-6 September 2001, Antwerpen, Belgium. 631-633.
- Weiland, P., 2003. Production and energetic use of biogas from energy crops and wastes in Germany. *Applied Biochemistry and Biotechnology,* 109, pp. 263-274.
- Weiland, P., 2006. Biomass digestion in agriculture: a successful pathway for the energy production and waste treatment in Germany. *Engineering in Life Sciences,* 6, pp. 302-309.
- Weiland, P., 2010. Biogas production: Current state and perspectives. *Appllied Microbiology Biotechnology* 85, pp. 849-860.
- Yen, H. W., and Brune, D. E., 2007. Anaerobic co-digestion of algal sludge and waste paper to produce methane. *Bioresource Technology.* 98, pp. 130-134.
- Yu, H. W., Samani, Z., Hanson, A., and Smith, G., 2002. Energy recovery from grass using two phase anaerobic digestion. *Waste Management,* 22,pp. 1-5.
- Zamalloa, C., Vulsteke, E., Albrecht, J., and Verstraete, W., 2011. The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource Technology,* pp. 1149-1158.
- Zhong, W., et al., 2012. Biogas productivity by co-digesting Taihu blue algae with corn straw as an external carbon source. *Bioresource Technology,* pp. 281-286.
- Zieminski, K., and Frac, M., 2012. Methane fermentation process as anaerobic digestion of biomass: Transformations, stages and microorganisms. *African Journal Biotechnology,* 11, pp. 4127-4139.