Bulgarian Journal of Agricultural Science, 19 (No 1) 2013, 1-14
Agricultural Academy

CURRENT STATE AND FUTURE OF BIOGAS AND DIGESTATE PRODUCTION

A. COMPARETTI*, P. FEBO, C. GRECO and S. ORLANDO
Dipartimento dei Sistemi Agro-Ambientali, Università degli Studi di Palermo Viale delle Scienze, Building 4, 90128 Palermo, Italy

Abstract

COMPARETTI, A., P. FEBO, C. GRECO and S. ORLANDO, 2013. Current state and future of biogas and digestate production. *Bulg. J. Agric. Sci.,* 19: 1-14

Over the past few years, the worldwide cost of energy has increased significantly, due to a growing global demand for energy and the decreasing availability of fossil fuel sources. Many countries are adopting environmental policies promoting the production and consumption of alternative, sustainable and renewable energy sources. Among these sources is green energy production through the anaerobic digestion of agricultural feedstock, like animal manure and food industry by-products, mainly aimed at producing biogas. Nevertheless, only a very small part of the biogas potential is currently used, while many European countries are facing huge problems caused by the overproduction of organic waste from industry, agriculture and households.

Biogas production is an excellent way of using organic waste for energy generation, followed by the recycling of the digested substratum (digestate) as fertiliser.

Many factors, like chemical composition and pH of raw materials, environmental temperature and microbial composition, influence the efficiency and reliability of the anaerobic digestion process.

This paper reviews the current state and perspectives of biogas and digestate production, including the above factors influencing the biogas and digestate yields of anaerobic digestion.

Key words: organic waste; anaerobic digestion; co-digestion; biogas; digestate

Abbreviations: Anaerobic Digestion (AD); Commonwealth of Independent States (CIS); European Biomass Association (AEBIOM); Organic Fraction of Municipal Solid Waste (OFMSW); Life Cycle Assessment (LCA); Combined Heat and Power (CHP); High Efficiency Particulate Air (HEPA)

Fossil and Renewable Energy Sources

Today the global energy supply is highly dependent on fossil sources (i.e. crude oil, lignite, hard coal, natural gas). According to the current energy policies and management, world market energy consumption is forecast to increase by 44% from 2006 (497 EJ) to 2030 (715 EJ) (IEO, 2009). Currently world economies are dependent on crude oil. Scientists disagree with each other on how long this fossil resource will be available but, according to some research, “peak oil production” (defined as “the time when the maximum rate of global crude oil production is reached, after which the production rate begins its final decline”) has already occurred or is expected to occur within the immediate future (Al Seadi et al., 2008).

The use of biomass for energy production (i.e. bioenergy) is deemed to be one of the most promising alternative, sustainable and renewable energy sources (Cherubini and Strømman, 2011).

The process is called AD and consists of a series of metabolic reactions (i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis), performed by a wide range

E-mail: antonio.comparetti@unipa.it; pierluigi.febo@unipa.it, carlo.greco@unipa.it; santo.orlando@unipa.it

of microorganisms and producing a gas mainly containing methane (CH_4) (biogas) and a digested substratum (digestate), that can be used as organic fertiliser or raw material for biofertilisers (Themelis and Ulloa, 2007).

Unlike fossil fuels, biogas from AD is permanently renewable, as it is produced from biomass, which is a living form of storage of solar energy through photosynthesis (Al Seadi et al., 2008).

World pollution prevention targets, the objectives of the Kyoto agreement, as well as the problems of human and animal health and food safety, require increasingly sustainable solutions for handling and recycling organic waste. In the context the biogas produced through the AD of animal manure, combined with pre- and/or post-treatment technologies, play an increasingly important role (Holm-Nielsen et al., 2009).

AD technology has developed rapidly, so that it can currently compete with aerobic technology, particularly for treating industrial wastewater and organic solid waste with high organic matter content (Kacprzak et al., 2010). Nevertheless, only a very small part of the biogas potential is used, while many countries are facing huge problems related to the overproduction of organic waste from industry, agriculture and households.

History and Current State of World Anaerobic Digestion

The use of wastewater and renewable resources for energy supply was known to the Sumerians, who practiced anaerobic cleansing of waste in 3000 BC.

In 1776, Alessandro Volta collected gas from Lake Como in order to examine it.

In 1868, Béchamp discovered that a mixed population of microorganisms is required to convert ethanol into methane (Deublein and Steinhauser, 2008).

In the early 1990s, both commercial and pilot AD plants were designed and built, so that the AD of organic waste became known at world level (Karagiannidis and Perkoulidis, 2009).

Nowadays thousands of biogas plants operate in Europe as well as in other parts of the world (Al Seadi et al., 2008). About 2.5 million of biogas plants operate in India, while China plans to build 200 million biogas plants by 2020. Recently the building and operation of agricultural biogas plants has started in Northern America (United States and Canada) and in Latin America (Argentina, Peru, Brazil, Chile and Mexico). Nowadays about 600 plants exist in the US, of which 100 are in the agricultural sector and 500 at landfills. In the CIS more than 70 plants have been built in Russia, more than 30 in Kazakhstan and 1 plant in the Ukraine, where about 3000 biogas plants are planned for biogas production (Deublein and Steinhauser, 2008).

Current state of anaerobic digestion in Europe

In 2010 three major biogas production channels, where methanisation plants designed for energy conversion are operational, can be distinguished in Europe: landfills (26.8%), urban wastewater and industrial effluent treatment plants (9.8%) and stores of other raw materials (63.4%). At the stores of other raw materials, methanisation plants are used on farms for digesting crop biomass, in the food processing industry for transforming by-products, at household level for converting waste and on green for treating cutting residues, besides multi-product co-digestion plants. The injection of biomethane (purified biogas) into the natural gas grid is spreading in countries like Germany, Sweden and the Netherlands.

The AEBIOM estimates that in 2020 the European production of biomass-based energy could be increased to 220 Mtoe. The highest potential biogas production is from crop biomass, in agriculture. The high growth in biogas production is due, above all, to the high increase which took place in Germany, where 7470 biogas plants are operational. The United Kingdom, the second EU biogas producer, has chosen energy production from landfill biogas. In 2010 in France, biogas was produced at 68 landfills (EurobObserv'ER, 2011).

Current State of Anaerobic Digestion in Italy

In 2010 Italy was the third European biogas producer, having a primary energy production of 478.5 ktoe (EurobObserv'ER, 2011). Italian biogas plants are mainly fed with animal manure and crop biomass, especially cereal silage and maize (Dinuccio et al., 2010). Nowadays high quantities of food industry by-products are unmarketable and, therefore, transferred to landfills, apart from cereal straw, which remains on the fields after harvest (ITABIA, 2003). These biomasses are suitable for use in AD plants (Schievano et al., 2009) and could replace the above food crops for energy production (Balsari et al., 2009; Amon et al., 2009).

The implementation of legislation promoting biogas production in agriculture is responsible for the fast growth of Italian biogas plants (EurobObserv'ER, 2011). In fact, in 2011 in Italy there were 709 biogas plants, of which 494 (313 operational, producing 209 MW, and 181 at the planning stage, able to produce 147 MW, for a total potential energy production of 356 MW) use livestock effluents, energy crops, organic residues, food industry by-products, sewage sludge and OFMSW and 215 (197 operational, producing 274 MW, and 18 at the planning stage, able to produce 19 MW, for a total potential energy production of 293 MW) collect landfill biogas (Fabbri et al., 2011).

Raw Materials and Products of Anaerobic Digestion

According to the European Waste Catalogue, in Europe the most common biomass categories used for biogas production are animal manure and slurry, as well as crop residues and by-products, digestible organic waste from food industry (of vegetable and animal origin), OFMSW and the organic fraction from catering (of vegetable and animal origin), sewage sludge and dedicated energy crops (like maize, miscanthus, sorghum, clover) (Al Seadi et al., 2008).

The chemical composition of biogas and the methane yield depend on the feedstock type, the digestion equipment and the hydraulic retention time, which is the period during which the bioreactor is filled in with the feedstock (Weiland, 2010).

In recent years, a new category of AD feedstock has been tested in many countries. Dedicated energy crops, i. e. herbaceous plants (like grass, maize and rape) and woody ones (like willow, poplar and oak), have been specifically cultivated for energy (biogas) production. However, woody crops need special delignification pre-treatment before AD (Al Seadi et al., 2008), as they tend to have high cellulose or lignin content: pre-treatment can physically, thermally and/or chemically break down these polymers. Thermal pre-treatment causes thermal hydrolysis and, therefore, increase methane production. Additives can increase the production rate of a bioreactor or the start-up speed, but their additional cost must be always balanced against the increased efficiency of the process. Alkali treatment can be advantageous when using plant materials for AD (Ward et al., 2008). Thermochemical pre-treatment uses a combination of heat and chemicals, in order to reduce particle size and, therefore, increase solubilisation. EU Regulation on Animal By-Products requires particle size lower than 12 mm for sanitisation, through heating at 70°C for one hour, which has been successful in reducing pathogens, like *Salmonella* spp., to undetectable levels (Paavola et al., 2006). However, pre-treatment of feedstock can increase biogas production, reduce volatile solids (Tiehm et al., 2001) and increase solubilisation (Tanaka et al., 1997).

The AD of organic raw materials converts organic matter into biogas and digestate (Tani et al., 2006; Zhang et al., 2007).

Biogas generally consists of a mixture of methane (CH_4) (48-65%), carbon dioxide (CO_2) (36-41%), nitrogen (up to 17%), oxygen (lower than 1%), hydrogen sulphide (H_2S) (32-169 ppm) and traces of other gases (Ward et al., 2008).

Digestate is the decomposed substratum, rich in macro- and micro-nutrients and, therefore, suitable for use as plant fertiliser or raw material for biofertilisers.

Anaerobic Digestion Factors

The AD of organic raw materials is a complex process, involving a number of different degradation steps. The microorganisms participating in this process are specific to each step with different environmental requirements (Khalid et al., 2011).

The growth and activity of anaerobic microorganisms and, therefore, the AD efficiency (in terms of biogas and digestate yields) and reliability are influenced by many critical factors: type, chemical composition (water and nutrient content, e.g. nitrogen, carbon source, C/N ratio), concentration and pH of raw materials; absence of oxygen; microbial composition; (constant) environmental temperature; presence and amounts of inhibitors (like ammonia); toxic compounds; concentration of intermediate products (like volatile fatty acids); bioreactor design and stirring intensity (Al Seadi et al., 2008; Behera et al., 2010; Jeong et al., 2010; Khalid et al., 2011).

All these factors have to be considered in order to obtain environmentally friendly and sustainable energy production from biogas (Hartmann, 2006).

Water Content

Even if the high water content of raw materials usually facilitates the AD process, it is difficult to keep the same availability of water throughout the digestion cycle (Hernandez-Berriel et al., 2008). It has been reported that the highest methane production rate occurs at a water content of 60-80% (Bouallagui et al., 2003). Hernandez-Berriel et al. (2008) studied methanogenesis reactions during AD at different water contents, i.e. 70% and 80%: in both cases, they found that the methanogenic phase begins around day 70. However, bioreactors working at water content lower than 70% produce a denser digestate, in order to obtain a higher methane production rate (Khalid et al., 2011).

Nutrient Content

Macronutrients, i.e. carbon, nitrogen, phosphor and sulphur, are important for the survival and growth of AD microorganisms, as well as microelements (trace elements), like iron, nickel, cobalt, selenium, molybdenum and tungsten (Al Seadi et al., 2008). The optimal ratio of the macronutrients carbon, nitrogen, phosphor and sulphur (C:N:P:S) is considered to be 600:15:5:1 (Al Seadi et al., 2008), while that sufficient for methanisation is considered to be 600:15:5:3 (Fricke et al., 2007).

Carbon Source

The rate of AD process is influenced by the type, availability and complexity of the substratum (Ghaniyari-Benis et al., 2010). Different types of carbon source support different groups of microorganisms.

Therefore, before starting a digestion process, the chemical composition of the substratum (carbohydrate, lipid, protein and fibre content) must be determined (Lesteur et al., 2009; Zhao et al., 2010).

Starch can also be used as an effective cheap substratum for biogas production, compared with sucrose and glucose (Su et al., 2009).

It has been reported that the initial concentration and total solid content of the substratum in the bioreactor can significantly influence the performance of AD and the amount of methane produced during this process (Fernandez et al., 2008).

Nitrogen Content

Nitrogen is essential for protein synthesis and is mainly required as a nutrient by microorganisms during AD (Kayhanian and Rich, 1995). Nitrogenous compounds in organic waste are usually proteins, which are converted into ammonium during AD (Sawayama et al., 2004). In the form of ammonium, nitrogen contributes to the stabilisation of pH inside the bioreactor where the process is taking place. Microorganisms absorb ammonium for producing new cell mass (Fricke et al., 2007).

C/N Ratio

The C/N ratio of organic raw materials plays a crucial role during the AD process (Cuetos et al., 2008).

A C/N ratio of 20-30 may provide enough nitrogen for the process (Weiland, 2006). Bouallagui et al. (2009a) suggested that a C/N ratio of 22-25 seemed to be optimal for the AD of fruit and vegetable waste, while Guermoud et al. (2009) and Lee et al. (2009a) reported that the optimal C/N ratio for the anaerobic degradation of organic waste is 20-35.

In order to improve the C/N ratio and bacteria nutrition, co-digestion of organic mixtures is performed (Cuetos et al., 2008).

pH

The pH value of the AD substratum influences the growth of methanogenic microorganisms and the dissociation of some compounds relevant for the AD process, i.e. ammonia, hydrogen sulphide and organic acids (Al Seadi et al., 2008).

Various researchers have reported a range of pH values suitable for AD, even if the optimal pH for methanogenesis was about 7.0 (Huber et al., 1982; Yang and Okos, 1987). Lee et al. (2009a) reported that an efficient methanogenesis inside an anaerobic digester occurs at a pH of 6.5-8.2, while hydrolysis and acidogenesis occur at a pH of 5.5 and 6.5, respectively (Kim et al., 2003). Other experiences show that methane formation takes place within a relatively narrow pH range, between 5.5 and 8.5 ca., with an optimal range of between 7.0 and 8.0 for most methanogens (Al Seadi et al., 2008).

Microbial Composition

The process of anaerobic decomposition, consisting of metabolic reactions, i.e. hydrolysis, acidogenesis, acetogenesis and methanogenesis (Park et al., 2005; Charles et al., 2009), can be catalysed by a wide range of microorganisms, able to convert complex macromolecules into low molecular weight compounds. Therefore, an inoculum source is crucial for the optimisation of the waste/inoculum ratio (Lopes et al., 2004; Forster-Carneiro et al., 2007). A wide range of microbial communities has been reported to be involved in the anaerobic decomposition process of organic waste (Lastella et al., 2002; Lata et al., 2002). Several anaerobic bacteria (Jingura and Matengaifa, 2009) often perform the process of biogas production from organic waste (Jingura and Matengaifa, 2009).

Fricke et al. (2007) reported that heterotrophic microorganisms probably decompose organic matter. Lee et al. (2009b) reported that the *Clostridium* species are the most common degraders under anaerobic conditions. According to Ike et al. (2010), a group of microorganisms, i.e. *Actinomyces*, *Thermomonospora*, *Ralstonia* and *Shewanella* spp., catalyse the degradation of food waste into volatile fatty acids, while *Methanosarcina* and *Methanobrevibacter*/*Methanobacterium* spp. mainly contribute to methane production. Trzcinski et al. (2010) found the hydrogenotrophic species (mainly *Methanobrevibacter* spp., *M. formicicum* and *Methanosarcina* spp.) active in methane synthesis.

Environmental Temperature

The AD process can take place at different temperatures, divided into three ranges: psychrophilic (lower than 25°C), mesophilic (25-45°C) and thermophilic (45-70°C) (Al Seadi et al., 2008).

The process temperature is directly correlated with the hydraulic retention time (Al Seadi et al., 2008).

Many modern biogas plants operate at thermophilic temperatures, as the thermophilic process provides many advantages, like a faster degradation rate of organic waste, higher biomass and biogas production, less effluent viscosity, higher pathogen destruction (Zhu et al., 2009). Ward et al. (2008) have reported optimal growth temperatures for some methanogenic bacteria: 37-45°C for mesophilic *Methanobacterium* spp., 37-40°C for *Methanobrevibacter* spp., 35-40°C for *Methanolobus*, *Methanococcus*, *Methanoculleus* and *Methanospirillum* spp., 30-40°C for *Methanoplanus* and *Methanocorpusculum* spp. and 50-55°C for thermophilic *Methanohalobium* and *Methanosarcina* spp. (Khalid et al., 2011). Ammonia toxicity and solubility of various compounds (NH_3, H_2, CH_4, H_2S and volatile fatty acids) depend on the process temperature (Angelidaki, 2004). Many researchers have reported significant effects of the temperature on microbial communities, process kinetics and stability and methane yield (Dela-Rubia et al., 2002; Bouallagui et al., 2009b; Riau et al., 2010).

Inhibitors

A high concentration of ammonia may inhibit the biological process, and concentrations of this nitrogenous compound higher than 100 mM ca. inhibit methanogenesis (Fricke et al., 2007). Therefore, methanogenic bacteria are particularly sensitive to ammonia inhibition. In order to prevent the ammonia inhibitory effect, its concentration should be kept lower than 80 mg/l (Al Seadi et al., 2008).

Toxic Compounds

Another factor influencing the activity of anaerobic microorganisms is the presence of toxic compounds. They can be transferred to the bioreactor together with the feedstock, or generated during the AD process (Al Seadi et al., 2008).

Intermediate Products

The stability of the AD process is proved by the concentration of intermediate products, like volatile fatty acids (acetate, propionate, butyrate, lactate), produced during acidogenesis. For example, animal manure has a surplus of alkalinity, which means that the accumulation of volatile fatty acids should exceed a certain level before this can be detected, due to a significant decrease of pH (Al Seadi et al., 2008).

Biogas and Methane Yields of Organic Waste Anaerobic Digestion

The values of biogas and methane average yields of the AD of several types of organic waste are shown in Figure 1 (Al Seadi et al., 2008; CTI, 2007). The biogas yield is highly variable among the various raw materials: the highest average biogas yield (202 m^3 t^{-1}) is obtained from maize silage, while the lowest (10 m^3 t^{-1}) comes from slurry. The methane average yield of all types of organic waste is higher than 50%, and in 2 cases higher than 60%, i.e. for liquid pig manure (65%) and distiller grain (61%).

Advantages of Organic Waste Anaerobic Digestion

Biogas production is an excellent way of using organic waste for energy generation, followed by the recycling of the digestate as fertiliser.

Among the advantages of AD, Ward et al. (2008) described the potential of this process for reducing environmental pollution: the sealed environment of the process prevents the emission of methane into the atmosphere, while methane burning releases carbon-neutral carbon dioxide (having no net effect on atmospheric carbon dioxide and other greenhouse gases).

In comparison with fossil fuels, biogas only contributes marginally to ozone depletion and acid rain (Nath and Das, 2004).

However, the impact mitigation may be reduced due to the energy and materials consumed for cultivation (cf. silage of maize and/or grass and/or whole wheat plants) and the transport of feedstock. Additional emissions also arise from biogas plant operation, biogas use and transportation and digestate disposal (Poeschl et al., 2012).

Moreover, a wide range of raw materials, like agricultural, industrial and municipal waste, besides plant residues, can be used for AD (Khalid et al., 2011).

At the same time, AD provides biogas and organic fertiliser or raw material for biofertilisers.

Organic waste having a low nutrient content can be degraded through co-digestion with other raw materials inside the anaerobic bioreactors.

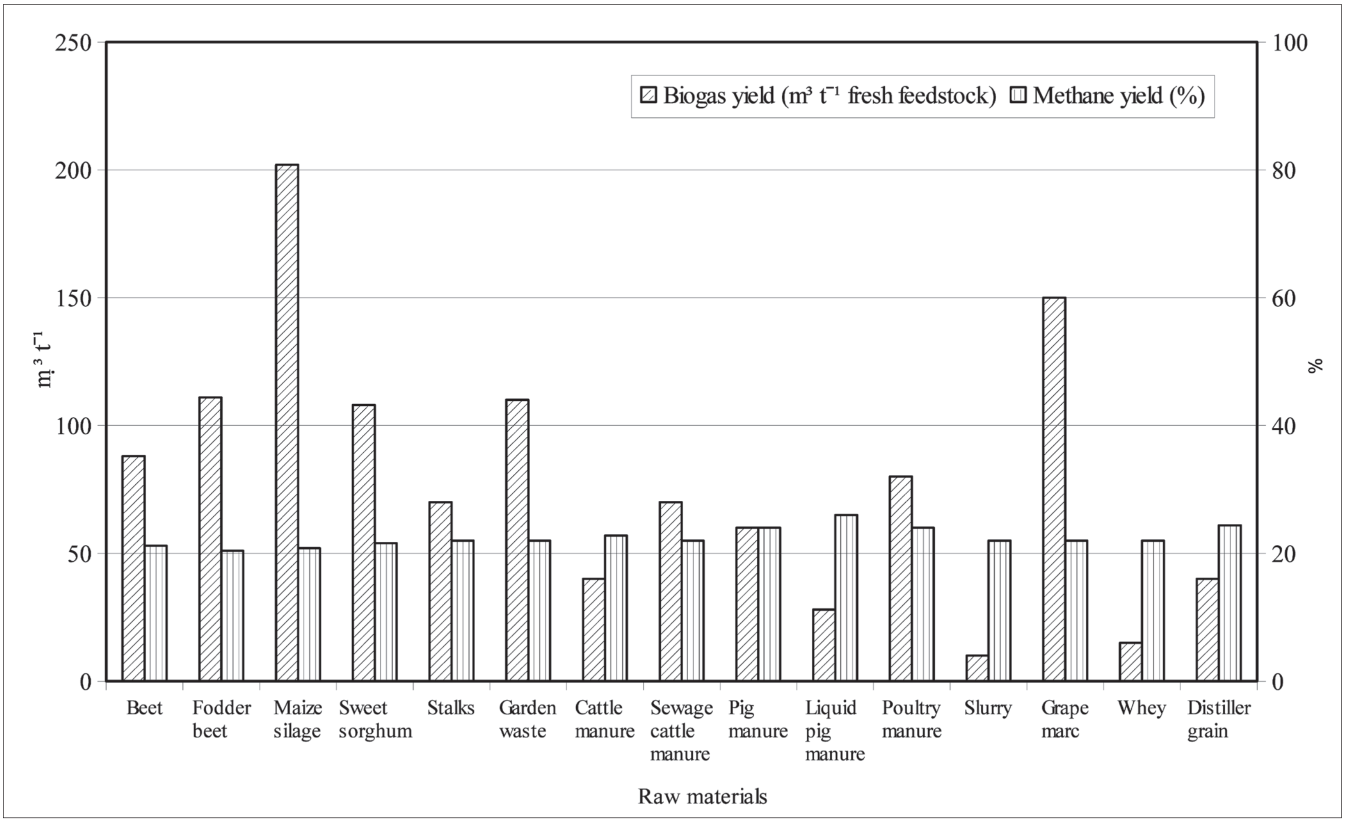

Fig. 1. Biogas and methane average yields of the anaerobic digestion of several types of organic waste (Al Seadi et al., 2008; CTI, 2007)

The AD process is able to inactivate weed seeds, bacteria (like *Salmonella* spp., *Escherichia coli*, *Listeria* spp.), viruses, fungi and other parasites in the feedstock and it, therefore, produces a digestate more suitable to be used as fertiliser (Sahlström, 2003; Strauch and Philipp, 2000).

AD also results in a significant reduction of bad smells (up to 80%) and in a positive change in the composition of odours (Weiland, 2010).

Anaerobic Co-digestion

Anaerobic co-digestion, also called “co-fermentation”, is a waste treatment method, during which different raw materials are mixed and treated together. This technology is increasingly applied, at the same time, to different solid and liquid organic waste (Agdag and Sponza, 2007; Khalid et al., 2011), as shown in Table 1. Anaerobic co-digestion, due to the positive synergy between raw materials having different C/N ratios, supplies missing nutrients to bacteria and, therefore, increases biogas yield. This method is mainly used for the wet process but also for dry treatment (Mata-Alvarez, 2002).

Many types of waste and by-products from food industry (like fruit and vegetable pulps, oil seed residues, overlaid foodstuff) are ideal co-substrata for digestion, because these raw materials are normally free of contaminants, pathogens and heavy metals. Instead, residues from restaurants, markets and municipal areas need pre-treatment to reduce particle size and separate contaminants, that can disturb the digestion process and the land application of the digestate. In addition, they need to be pasteurised at 70°C for one hour, in order to reduce the content of pathogenic microorganisms. The use of dedicated energy crops is another interesting option for co-digestion, because enough fallow agricultural land is available in many European countries for cultivation (Weiland, 2003). Olive mill effluents, macroalgae, waste from kitchens, slaughter houses and the meat processing industry were also investigated as co-substrata (Angelidaki and Ahring, 1997; Cecchi et al., 1993; Kübler et al., 2000; Brinkman, 1999;

Table 1
Biogas production rate and methane yield of the anaerobic co-digestion of different types of organic waste

Substratum	Co-substrata	Biogas production rate [l d^{-1}]	Methane yield [l kg^{-1} VS a]	Comments	**References**
Cattle excreta	Olive mill waste	1.10	179	Co-digestion produced 337% higher biogas than excreta.	Goberna et al. (2010)
Cattle manure	Crop waste and energy crops	2.70	620	A significantly increased biogas production from co-digestion was observed.	Cavinato et al. (2010)
Fruit and vegetable waste	Abattoir wastewater	2.53	611	The addition of abattoir wastewater to the feedstock increased biogas yield up to 51.5%	Bouallagui et al. (2009a)
Pig manure	Fish and bio-diesel waste	16.4	620	A higher biogas production rate was obtained from co-digestion.	Alvarez et al. (2010)
Potato waste	Sugar beet waste	1.63	680	Co-digestion increased methane yield up to 62%, compared with the digestion of potato waste.	Parawira et al. (2004)

[a] VS: Volatile Solids.

Mata-Alvarez et al., 2000). Anaerobic co-digestion of mixtures including food industry residues and animal manure have been previously documented (Callaghan et al., 2002; Kaparaju and Rintala, 2003) and, of these mixtures, particular interest was paid to the co-digestion of animal manure and whey (Gelegenis et al., 2007; Ghaly, 1996) or maize silage (Amon et al., 2007) or sugar beet (Umetsu et al., 2006). Several authors (Ghaly and Pyke, 1991; Lo and Liao, 1986; Yan et al., 1989) have documented anaerobic treatment of cheese whey for biogas production (Ghaly and Pyke, 1991; Lo and Liao, 1986; Yan et al., 1989). Some studies have shown that, in lab-scale bio-reactors, the co-digestion of cheese whey together with other substrata (i.e. maize silage, beet pulp, carrot residues and glycerine fraction) can be advantageous (Kacprzak et al., 2010).

In Northern Italy biogas plants currently co-digest animal manure together with dedicated energy crops, like maize, while in the Southern Italy future biogas plants could co-digest food industry by-products, i.e. pomace and wastewater from olive oil mills or solid waste from the citrus industry or cereal straw or poultry manure (instead of animal manure), together with alternative crops like Italian sainfoin (*Hedysarum coronarium*) (instead of maize) (Mattirolo, 2012).

Life Cycle Assessment

LCA is the evaluation of a production system for its life cycle (ISO 14040), considering the resources and energy inputs and outputs generated during the production cycle until the end. In other words LCA is a framework for estimating the environmental impact of the life cycle of a product (Rebitzer et al., 2004), i.e. from raw material acquisition, through the production and use phases, to waste management at the end of life. LCA interpretation is provided by indicators, which highlight the environmental burden of a product.

Specifically, an integrated assessment of biogas technology options is required, and this LCA is based on multiple feedstocks used for the AD process, combined with different potential biogas applications and digestate processing and handling methods (Poeschl et al., 2012).

Bioreactors Used for Anaerobic Digestion

In recent years a range of new bioreactor or biodigester designs have been developed, as shown in Table 2 (Bouallagui et al., 2003; Mumme et al., 2010; Xing et al., 2010). Several types of bioreactor are currently used, but the three most common groups include batch bioreactors, "one stage continuously fed systems", "two stages" or "multi-stage continuously fed systems" (Weiland, 2010).

The batch bioreactor is the simplest one, filled with the feedstock and left for a period, called hydraulic retention time, after which it is emptied. An anaerobic batch reactor can perform rapid digestion, using simple and cheap equipment, and allows easy assessment of the digestion rate (Weiland, 2006; Parawira et al., 2004).

A "one-stage continuously fed system" is a bioreactor where all the bio-chemical reactions take place.

A "two-stage" or "multi-stage continuously fed system" is a bioreactor where the entire bio-chemical reactions (i.e. hydrolysis, acidification, acetogenesis and methanogenesis) take place separately (Ward et al., 2008). The "two-stage continuously fed system" is considered a promising bioreactor for treating organic waste with high

Table 2
Different types of bio-reactor used for anaerobic digestion

Bio-reactor	Substratum	Organic loading rate [kg m-3 d-1]	Comments	References
Batch bio-reactor	Fruit and vegetable waste and abattoir wastewater	2.6	Decreased biogas production was observed, due to a high amount of free ammonia at high organic loading rate.	Bouallagui et al. (2009b)
One-stage continuously fed system	Kitchen waste	8.0	The performance and biogas production rate was higher than single reactors.	Guo et al. (2011)
Two-stage semi-continuously fed system	Olive mill wastewater and pomace	14	The best methane yield, soluble COD, phenol removal efficiency and effluent quality were observed.	Fezzani and Cheikh (2010)
Two-stage continuously fed system	Organic waste	3.0	11% higher energy was achieved, compared with a one-stage continuously fed system.	Luo et al. (2011)
Multi-stage continuously fed system	Food industry waste	17	A methane yield of 360 l kg^{-1} after a 40-day hydraulic retention time was observed.	Ike et al. (2010)
Self mixing bio-reactor	Poultry litter	16	High organic loading rate and biomethanisation were observed.	Rao et al. (2011)
Up flow Anaerobic Solid State bio-reactor (UASS)	Maize silage and straw	17	The highest methane yield of solid biomass digestion was observed.	Mumme et al. (2010)

efficiency, both in terms of degradation yield and biogas production (Fezzani and Cheikh, 2010).

Bioreactors are also classified as “wet” or “dry” solid waste digesters. According to Ward et al. (2008), wet bioreactors have a total solid content of 16% or less, while dry biodigesters have a total solid content of 22-40%, with the intermediate rating called “semi-dry”. According to Karagiannidis and Perkoulidis (2009), wet bioreactors have a dry matter content of 10-25%, while dry biodigesters have a dry matter content of 30-40%.

Bioreactors are also classified as thermophilic and mesophilic, based on their operating temperature (Karagiannidis and Perkoulidis, 2009; Kuo and Cheng, 2007).

Nowadays wet digestion processes are widespread in the agricultural sector (Weiland, 2010). Many types and concepts of agricultural biogas plants are implemented (Schulz and Eder, 2001). However, the most common bioreactor type used for wet digestion is the vertical continuously stirred tank digester (Gemmeke et al., 2009). Another approach is to apply continuous dry digestion processes to raw materials with a dry matter content of more than 25% (Weiland et al., 2009).

Biogas Applications

Immediately after production, biogas has to be cooled, drained and dried and usually cleaned, because of its hydrogen sulphide (H_2S) content (Holm-Nielsen et al., 2009). Nowadays the removal of H_2S is mainly carried out through biological desulfurisation (Schneider et al., 2002). Levels of H_2S content in biogas with more than 300-500 ppm damage the energy conversion equipment (Holm-Nielsen and Al Seadi, 2004). Biological cleaning reduces the hydrogen sulphide content to a level lower than 100 ppm (Holm-Nielsen et al., 2009).

Both raw and upgraded biogas can be used in several ways.

Biogas is a combustible gas, which is generally used as a source for co-generation, also called CHP production, for simultaneously producing electricity and heat (Ward et al., 2008), by means of gas or dual fuel engines.

Micro gas turbines and fuel cells are alternatives to co-generation. Micro gas turbines result in lower electrical efficiency (25-31%) but high load flexibility and long maintenance intervals. A major advantage of this use, compared with reciprocal engines, is the availability of the exhaust heat (still having at least 270°C after the heat recuperator), which could be used for steam production in other processes (Schmid et al., 2005). Fuel cells result in higher electrical efficiency but need efficient gas cleaning, because the used catalysts are very sensitive to impurities (Ahrens and Weiland, 2007). The various fuel cell types work at highly variable temperatures, from 80 to 800°C. However, the investment costs related to the above two technologies are much higher than that of co-generation.

Biogas injection into the natural gas grid and/or its use as vehicle fuel has become increasingly important, because these applications make biogas itself usable throughout the year, resulting in higher energy efficiency. In many EU countries access to the natural gas grid is guaranteed by state regulations. Countries like Germany, Sweden and Switzerland have defined quality standards for biogas injection into the natural gas grid. In fact, all gas contaminants like carbon dioxide must be removed and the gas must have methane content higher than 95%, in order to fulfil the quality requirements of the different gas appliances. In order to ensure that biomethane does not contain bacteria and moulds, which could create unacceptable risks for human health and equipment, the application of HEPA filters is discussed. The use of methane in the transport sector is widespread in Sweden and Switzerland. The biogas is stored at the pressure of 200-250 bars in gas bottles (Weiland, 2010).

Various technologies can be applied to increase the methane content of biogas (Persson et al., 2006).

The most common methods for removing carbon dioxide from biogas are scrubbing using water or organic solvents, like polyethylene glycol (Kapdi et al., 2005), as well as pressure swing absorption, using activated carbon or molecular sieves (Schulte-Schulze Berndt, 2005).

Chemical washing by alkanol amines like monoethanolamine or dimethylethanolamine, as well as membrane technologies and cryogenic separation at low temperature are less frequently used. During the removal of carbon dioxide from the gas stream, small amounts of methane are also removed. These methane losses must be kept low for both environmental and economical reasons, since methane is a greenhouse gas 23 times stronger than CO_2 (Weiland, 2010).

Digestate Applications

The digestate can be accurately dosed and integrated in a fertilisation plan, in order to reduce the application of additional mineral nitrogen fertilisers. In fact, AD also contributes to significant reduction of bad smells and positively changes the composition of odours (Weiland, 2010). The application of the digestate as fertiliser improves veterinary safety, compared with the application of untreated manure and slurry.

In order to become suitable for use as fertiliser, the digestate is submitted to a controlled sanitation process (Al Seadi et al., 2008). Depending on the type of feedstock used, sanitation can be provided by the AD process itself, through a minimum guaranteed hydraulic retention time of the substratum inside the bioreactor, at thermophilic temperature, or it can be carried out in a separate step, through pasteurisation or pressure sterilisation.

The AD process is also able to deactivate weed seeds, bacteria, viruses, fungi and other parasites in the feedstock and, therefore, make the digestate more suitable for use as a fertiliser (Sahlström, 2003; Strauch and Philipp, 2000).

In some European countries, the digestate must be stored inside covered tanks (Palm, 2008). The covering of storage tanks offers an opportunity to reduce gaseous emissions into the atmosphere (Menardo et al., 2011) and to capture residual digestate methane (Kaparaju and Rintala, 2003). In fact, an additional methane yield of 15% has been measured during digestate post-methanisation (Weiland, 2003). Döhler et al. (2009) estimated that the digestate storage phase accounts for approximately 27% of global CO_2eq. emissions generated during the AD process.

Future of Anaerobic Digestion

Fossil fuels are limited resources, concentrated in a few geographical areas of the Earth. This generates, for the countries outside these areas, a permanent state of dependency on imported energy. Most European countries are strongly dependent, on fossil imported fuels, from regions rich in fossil fuel sources, like Russia and the Middle East. The development and implementation of renewable energy sources, such as biogas from AD, based on national and regional biomasses, will increase the security of the national energy supply and reduce dependency on imported fuels.

Fighting global warming is one of the main priorities of European energy and environmental policies. The production and use of biogas from AD has the potential to comply, at the same time, with all the three main goals of the EU climate and energy package for 2020: to reduce greenhouse gas emissions by 20%; to improve energy efficiency by 20%; to generate 20% of energy consumption from renewable energy sources. A major part of renewable energy will be produced from European agriculture and forestry, through biomass conversion into gaseous, liquid and solid biofuels.

The AD cycle is an integrated system of resource use, organic waste treatment and nutrient recycling and redistribution, generating intertwined agricultural and environmental benefits, such as renewable energy production, cheap and environmentally healthy organic waste recycling, lower greenhouse gas emission, pathogen reduction through sanitation, increased fertilisation efficiency, lower nuisance from odours, and economical advantages for farmers. The success of AD will be derived from the availability at low cost of a broad range of biogas forms, which can be used for producing heat, steam, electricity and hydrogen and as a vehicle fuel (biomethane). Moreover, the AD process can be implemented, on both small and large scales, anywhere in the world, using many different raw materials, e.g. crops, grass, plant leaves, animal manure, fruit and vegetable waste, and algae. AD, therefore, may play a very crucial role in meeting the energy challenges of the future generation.

In order to ensure a unified European standard and, through this standard, the same quality and safety measures all over Europe, a EU regulation was adopted "laying down the health rules concerning animal by-products not intended for human consumption" (Commission of the European Communities, 2002). The aim of this regulation is to promote the biological treatment of organic waste in European countries, by harmonising national measures and regulations on organic waste management, in order to prevent negative environmental impact and ensure that the recycling of treated and untreated organic waste results in the improvement of agriculture (Holm-Nielsen et al., 2009).

References

Agdag, O. N. and D. T. Sponza, 2007. Co-digestion of mixed industrial sludge with municipal solid wastes in anaerobic simulated landfilling bioreactors. *J. Hazard. Mat.,* **140**: 75-85.

Ahrens, T. and P. Weiland, 2007. Biomethane for future mobility. *Landbauforschung Völkenrode*, **57**: 71-79.

Al Seadi, T., Rutz, D., Prassl, H., Köttner, M., Finsterwalder, T., Volk, S. and R. Janssen, 2008. *Biogas Handbook.* Published by University of Southern Denmark Esbjerg, Niels Bohrs Vej, DK-6700 Esbjerg, Denmark, pp. 9-10.

Alvarez, J. A., Otero, L. and J. M. Lema, 2010. A methodology for optimizing feed composition for anaerobic co-digestion of agro-industrial wastes. *Bioresource Technology*, **101**: 1153-1158.

Amon, T., Amon, B., Kryvoruchko, V., Zollitsch, W., Mayer, K. and L. Gruber, 2007. Biogas production from maize and dairy cattle manure - Influence of biomass composition on the methane yield. *Agriculture, Ecosystems and Environment*, **118**: 173-182.

Amon, T., Mayr, H., Eder, M., Hobbs, P., Rao Ravella, S., Roth, U., Niebaum, A., Doehler, H., Weiland, P., Abdoun, E., Moser, A., Lyson, M., Heiermann, M., Budde, J., Schattauer, A., Suarez, T., Moller, H., Ward, A., Hillen, F., Sulima, P., Oniszk-Polplawska, A., Krampe, P., Pastorek, Z., Kara, J., Mazancova, J., Von Dooren, H., Wim, C., Gioelli, F. and P. Balsari, 2009. EU-agro biogas project. In: *Proceedings of XXXIII CIOSTA - CIGR V Conference:* Technology and management to ensure sustainable agriculture, agro-systems, forestry and safety, Volume 2, Reggio Calabria, Italy, pp. 1081-1086.

Angelidaki, I. and B. K. Ahring, 1997. Codigestion of olive oil mill wastewaters with manure, household waste or sewage sludge. *Biodegradation*, **8** (4): 221-226.

Angelidaki, I., 2004. *Environmental Biotechnology. AD - Biogas Production*. Environment and Resources DTU, Technical University of Denmark.

Balsari, P., Menardo S., Gioelli, F. and E. Dinuccio, 2009. European project EU-agro biogas: Aims, objectives and first results obtained. In: *Proceedings of the* IX National Congress of the Italian Association of Agricultural Engineering - Research and innovation in engineering of agro-territorial bio systems, Ischia Porto (Naples), 12-16 September 2009.

Behera, S. K., Park, J. M., Kim, K. H. and H. Park, 2010. Methane production from food waste leachate in laboratory-scale simulated landfill. *Waste Management*, **30**: 1502-1508.

Bouallagui, H., Cheikh, R. B., Marouani, L. and M. Hamdi, 2003. Mesophilic biogas production from fruit and vegetable waste in tubular digester. *Bioresource Technology*, **86**: 85-89.

Bouallagui, H., Lahdheb, H., Romdan, E., Rachdi, B. and M. Hamdi, 2009a. Improvement of fruit and vegetable waste anaerobic digestion performance and stability with co-substrates addition. *Journal of Environmental Management*, **90**: 1844-1849.

Bouallagui, H., Rachdi, B., Gannoun, H. and M. Hamdi, 2009b. Mesophilic and thermophilic anaerobic co-digestion of abattoir wastewater and fruit and vegetable waste in anaerobic sequencing batch reactors. *Biodegradation*, **20**: 401-409.

Brinkman, J., 1999. Anaerobic digestion of mixed slurries from kitchens, slaughterhouses and meat processing industries. In: J. Mata Alvarez., A. Tilche and F. Cecchi (Editors), *Proceedings of the Second International Symposium on Anaerobic Digestion of Solid Waste,* Barcelona, 15-18 June, pp. 190-195.

Callaghan, F. J., Waste, D. A. J., Thayanity, K. and C. F. Forster, 2002. Continuous co-digestion of cattle slurry with fruit and vegetable wastes and chicken manure. *Biomass and Bioenergy*, **22**: 71-77.

Cavinato, C., Fatone, F., Bolzonella, D. and P. Pavan, 2010. Thermophilic anaerobic codigestion of cattle manure with agro-wastes and energy crops: comparison of pilot and full-scale experiences. *Bioresource Technology*, **101**: 545-550.

Cecchi, F., Vallini, G., Pavan, P., Bassetti, A. and J. Mata-Alvarez, 1993. Management of macroalgae from the Venice lagoon through anaerobic co-digestion and co-composting with municipal solid waste (MSW). *Water Science and Technology*, **27** (2): 159-168.

Charles, W., Walker, L. and R. Cord-Ruwisch, 2009. Effect of pre-aeration and inoculums on the start-up of batch thermophilic anaerobic digestion of municipal solid waste. *Bioresource Technology*, **100**: 2329-2335.

Cherubini, F. and A. H. Strømman, 2011. Life cycle assessment of bioenergy systems: State of the art and future challenges. *Bioresource Technology*, **102**: 437-451.

Commission of the European Communities, 2002. *Regulation No. 1774 of the European Parliament and of the Council: Laying Down the Health Rules Concerning Animal By-Products Not Intended for Human Consumption,* Brussels, October 2002.

CTI, Italian Thermal Engineering Committee, 2007. Energy and Environment within the project "*Valutazione delle potenzialità di diffusione di impianti di biogas aziendali e/o consortili alimentati a biomassa, residui agroalimentari e frazione organica dei rifiuti solidi urbani" [Evaluation of the potential dissemination of farm and / or consortium biogas plants fed by biomass, food wastes and the organic fraction of municipal solid waste] - INTERREG IIIA Italy - Switzerland* coordinated by Fojanini Foundation for Advanced Studies in Sondrio and implemented with the support of Lombardy Region DG Agriculture.

Cuetos, M. J., Gomez, X., Otero, M. and A. Moran, 2008. Anaerobic digestion of solid slaughterhouse waste (SHW) at laboratory scale: influence of co-digestion with the organic fraction of municipal solid waste (OFMSW). *Biochemical Engineering Journal*, **40**: 99-106.

Dela-Rubia, M. A., Perez, M., Romero, L. I. and D. Sales, 2002. Anaerobic mesophilic and thermophilic municipal sludge digestion. *Chemical and Biochemical Engineering*, **16**: 119-124.

Deublein, D. and A. Steinhauser, 2008. *Biogas from Waste and Renewable Resources. An Introduction.* WILEY-VCH Verlag GmbH and Co. KGaA, Weinheim.

Dinuccio, E., Balsari, P., Gioelli, F. and S. Menardo, 2010. Evaluation of the biogas productivity potential of some Italian agro-industrial biomasses. *Bioresource Technology*, **101**: 3780-3783.

Döhler, H., Niebaum, A., Roth, U., Amon, T., Balsari, P. and G. Friedl, 2009. Greenhouse gas emissions and mitigation costs in two European biogas plants. In: *Proceedings of the XXIII CIGR CIOSTA Conference*, Volume 1, Reggio Calabria, Italy, pp. 1115-1120.

EurobObserv'ER, 2011. *The State of Renewable Energies in Europe. 11th Report*.

Fabbri, C., Soldano and S. Piccinini. (C.R.P.A. Animal Production Research Center), 2011. Il biogas accelera la corsa verso gli obiettivi 2020. [The biogas accelerates the race towards 2020 targets]. *Supplemento a "L'Informatore Agrario"* [*Supplement to"The Agricultural Informer"]*, **26**: 15-19.

Fernandez, J., Perez, M. and L. I. Romero, 2008. Effect of substrate concentration on dry mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). *Bioresource Technology, **99**:* 6075-6080.

Fezzani, B. and R. B. Cheikh, 2010. Two-phase anaerobic co-digestion of olive mill wastes in semi-continuous digesters at mesophilic temperature. *Bioresource Technology*, **101**: 1628-1634.

Forster-Carneiro, T., Pérez, M., Romero, L. I. and D. Sales, 2007. Dry-thermophilic anaerobic digestion of organic fraction of the municipal solid waste: focusing on the inoculum sources. *Bioresource Technology*, **98**: 3195-3203.

Fricke, K., Santen, H., Wallmann, R., Huttner, A. and N. Dichtl, 2007. Operating problems in anaerobic digestion plants resulting from nitrogen in MSW. *Waste Management*, **27**: 30-43.

Gelegenis, J., Georgakakis, D., Angelidaki, I. and V. Mavris, 2007. Optimization of biogas production by co-digesting whey with diluted poultry manure. *Renewable Energy*, 32: 2147-2160.

Gemmeke, B., Rieger, C. and P. Weiland, 2009. *Biogas-Messprogramm II*, **61**, Biogasanlagen im Vergleich. FNR, Gülzow.

Ghaly, A. E., 1996. A comparative study of anaerobic digestion of acid cheese whey and dairy manure in a two-stage reactor. *Bioresource Technology*, **58**: 61-72.

Ghaly, A.E. and J.B. Pyke, 1991. Amelioration of methane yield in cheese whey fermentation by controlling the pH of the methanogenic stage. *Applied Biochemistry and Biotechnology*, **27**: 217-237.

Ghaniyari-Benis, S., Borja, R., Ali Monemian, S. and V. Goodarzi, 2009. Anaerobic treatment of synthetic medium-strength wastewater using a multistage biofilm reactor. *Bioresource Technology*, **100**: 1740-1745.

Goberna, M., Schoen, M.A., Sperl, D., Wett, W. and H. Insam, 2010. Mesophilic and thermophilic co-fermentation of cattle excreta and olive mill wastes in pilot anaerobic digesters. *Biomass Bioenergy*, **34**, 340-346.

Guermoud, N., Ouagjnia, F., Avdelmalek, F., Taleb, F., and A. Addou, 2009. Municipal solid waste in Mostagnem city (Western Algeria). *Waste Management*, **29**: 896-902.

Guo, L., Shi, Y., Zhang, P., Wu, L., Gai, G. S., Wang, H. and D. L. Xiao, 2011. Investigations, analysis and study on biogas utilization in cold region of North China. *Advanced Materials Research*: 183-185, 673-677.

Hartmann, J. K., 2006. *Life-cycle-assessment of Industrial Scale Biogas Plants.* Georg-August-Universität, Göttingen, Germany.

Hernandez-Berriel, M. C., Benavides, L. M., Perez, D. J. G., and O. B. Delgado, 2008. The effect of moisture regimes on the anaerobic degradation of municipal solid waste from Metepec (Mexico). *Waste Management*, **28**: 14-20.

Holm-Nielsen, J. B. and T. Al Seadi, 2004. *Manure-based biogas systems - Danish Experience in Resource Recovery and Reuse in Organic Solid Waste Management.* IWA Publishing, pp. 377-394. ISBN 1 84339 054X (Chapter 17).

Holm-Nielsen, J. B., Al Seadi, T. and P. Oleskowicz-Popiel, 2009. The future of anaerobic digestion and biogas utilization. *Bioresource Technology*, **100**: 5478-5484.

Huber, H., Thomm, M., Konig, H., Thies, G. and K.O. Stetter, 1982. Methanococeus thermolithotrophicus, a novel thermophilic lithotrophic methanogen. *Archives of Microbiology*, **132**: 47-50.

IEO, International Energy Outlook, 2009. *Energy Information Administration, Office of Integrated Analysis and Forecasting,* US Department of Energy, Washington, DC, p. 284.

ITABIA, Italian Biomass Association (2003). *Le biomasse per l'energia e l'ambiente [Biomasses for energy and environment]*, Report.

Ike, M., Inoue, D., Miyano, T., Liu, T. T., Sei, K., Soda, S. and S. Kadoshin, 2010. Microbial population dynamics during startup of a full-scale anaerobic digester treating industrial food waste in Kyoto eco-energy project. *Bioresource Technology*, **101**: 3952-3957.

Jeong, E., Kim, H., Nam, J., and H. Shin, 2010. Enhancement of bioenergy production and effluent quality by integrating optimized acidification with submerged anaerobic membrane bioreactor. *Bioresource Technology*, **101**: 1873-2976.

Jingura, R. M. and R. Matengaifa, 2009. Optimization of biogas production by anaerobic digestion for sustainable energy development in Zimbabwe. *Renewable and Sustainable Energy Reviews*, **13**: 1116-1120.

Kacprzak, A., Krzystek, L., and S. Ledakowicz, 2010. Co-digestion of agricultural and industrial wastes. *Chemical Papers*, **64** (2): 127-131.

Kaparaju, P. L. N., and J. A. Rintala, 2003. Effects of temperature on post-methanation of digested dairy cow manure in a farm-scale biogas production system. *Environmental Technology*, **24**: 1315-1321.

Kapdi, S. S., Vijay, V. K., Rajesh, S. K. and R. Prasad, 2005. Biogas scrubbing, compression and storage. *Renewable Energy*, **30**:1195-1202.

Karagiannidis, A. and G. Perkoulidis, 2009. A multi-criteria ranking of different technologies for the anaerobic digestion for energy recovery of the organic fraction of municipal solid wastes. *Bioresource Technology*, **100**: 2355-2360.

Kayhanian, M. and D. Rich, 1995. Pilot-scale high solids thermophilic anaerobic Digestion of municipal solid waste with an emphasis on nutrient requirements. *Biomass Bioenergy*, **8**: 433-444.

Khalid, A., Arshad, M., Anjum, M., Mahmood, T. and L. Dawson, 2011. The anaerobic digestion of solid organic waste. *Waste Management*, **31**: 1737-1744.

Kim, J., Park, C., Kim, T. H., Lee, M., Kim, S., Kim, S. W. and J. Lee, 2003. Effects of various pretreatments for enhanced anaerobic digestion with waste activated sludge. *Journal of Bioscience and Bioengineering*, **95**: 271-275.

Kübler, H., Hoppenheidt, K., Hirsch, P., Kottmair, A., Nimmrichter, R., Nordsieck, H., Mùcke, W. and M. Sweren, 2000. Full scale co-digestion of organic waste. *Water Science and Technology, **41(3)***: 195-202.

Kuo, W. and K. Cheng, 2007. Use of respirometer in evaluation of process and toxicity of thermophilic anaerobic digestion for treating kitchen waste. *Bioresource Technology*, **98**: 1805-1811.

Lastella, G., Testa, C., Cornacchia, G., Notornicola, M., Voltasio, F. and V. K. Sharma, 2002. Anaerbic digestion of semi-solid organic waste: biogas production and its purification. *Energy Conversion and Management*, **43**: 63-75.

Lata, K., Rajeshwari, K. V., Pant, D. C. and V. V. N. Kishore, 2002. Volatile fatty acid production during anaerobic mesophilic digestion of tea and vegetable market wastes. *World Journal of Microbiology and Biotechnology*, **18**: 589-592.

Lee, D. H., Behera, S. K., Kim, J. and H. S. Park, 2009a. Methane production potential of leachate generated from Korean food waste recycling facilities: a lab scale study. *Waste Management*, **29**: 876-882.

Lee, J., Song, J. and S. Hwang, 2009b. Effects of acid pre-treatment on bio hydrogen production and microbial communities during dark fermentation. *Bioresource Technology*, **100**: 1491-1493.

Lesteur, M., Bellon-Maurel, V., Gonzalez, C., Latrille, E., Roger, J. M., Junqua, G. and J.P. Steyer, 2010. Alternative methods for determining anaerobic biodegradability: a review. *Process Biochemistry*, **45**: 431-440.

Lo, K. V. and P. H. Liao, 1986. Digestion of cheese whey with anaerobic rotating biological contact reactor. *Biomass*, **10**: 243-252.

Lopes, W. S., Leite, V. D. and S. Prasad, 2004. Influence of inoculum on performance of anaerobic reactors for treating municipal solid waste. *Bioresource Technology*, **94**: 261-266.

Luo, G., Xie, L., Zhou, Q. and I. Angelidaki, 2011. Enhancement of bioenergy production from organic wastes by two-stage anaerobic hydrogen and methane production process. *Bioresource Technology*, **102** (18):8700-6.

Mata-Alvarez, J., 2002. *Biomethanization of the organic fraction of municipal solid wastes.*

Mata-Alvarez, J., Mace, S. and P. Llabres, 2000. Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. *Bioresource Technology*, **74** (1): 3-16.

Mattirolo, P. (2012). Costi e benefici dell'impiego dei sottoprodotti. [Costs and benefits of the use of by-products]. In: *Proceedings of the Conference "Biogas in Sicilia: un giacimento di energia" [Biogas in Sicily: a deposit of energy],* Vittoria (Ragusa) - EMAIA exhibition - AGREM, 31 March 2012. URL: http://www.agroenergia.eu/index.php?option=com_contentandview=articleandid=257and Itemid=264andlang=it

Menardo, S., Gioielli, F. and P. Balsari, 2011. The methane yield of digestate: Effect of organic loading rate, hydraulic retention time, and plant feeding. *Bioresource Technology*, **102:** 2348-2351.

Mumme, J., Linke, B. and R. Tölle, 2010. Novel upflow anaerobic solid-state (UASS) reactor. *Bioresource Technology*, **101**: 592-599.

Nath, K. and D. Das, 2004. Improvement of fermentative hydrogen production: various approaches. *Applied Microbiology and Biotechnology*, **65**: 520-529.

Paavola, T., Syvasalo, E. and J. Rintala, 2006. Co-digestion of manure and biowaste according to the EC animal by-products regulation and Finnish national regulations. *Water Science and Technology*, **53**, 223-231.

Palm, O., 2008. The quality of liquid and solid digestate from biogas plants and its application in agriculture. ENC/ORBIT e.V. workshop 2008. *The future for anaerobic digestion of organic waste in Europe.*

Parawira, W., Murto, M., Zvauya, R. and B. Mattiasson, 2004. Anaerobic batch digestion of solid potato waste alone and in combination with sugar beet leaves. *Renewable Energy*, **29**: 1811-1823.

Park, C., Lee, C., Kim, S., Chen, Y. and H. A. Chase, 2005. Upgrading of anaerobic digestion by incorporating two different hydrolysis processes. *Journal of Bioscience and Bioengineering*, **100**: 164-167.

Persson, M., Jönsson, O. and A. Wellinger, 2006. Biogas upgrading to vehicle fuel standards and grid injection. Brochure of IEA, Task 37 - *"Energy from Biogas and Landfill Gas"*.

Poeschl, M., Ward, S. and P. Owende, 2012. Environmental impacts of biogas deployment - Part I: life cycle inventory for evaluation of production process emissions to air. *Journal of Cleaner Production*, **24**: 168-183.

Rao, A. G., Prakash, S. S., Joseph, J., Reddy, A. R. and P. N. Sarma, 2011. Multi stage high rate biomethanation of poultry litter with self-mixed anaerobic digester. *Bioresource Technology*, **102**: 729-735.

Rebitzer, G., Ekvall, T. and R. Frischknecht, 2004. Life cycle assessment: part 1: framework, goal and scope definition, inventory analysis, and applications. *Environment International*, **30** (5): 701-720.

Riau, V., De la Rubia, M. A. and M. Pérez, 2010. Temperature-phased anaerobic digestion (TPAD) to obtain class A biosolids: a semi-continuous study. *Bioresource Technology*, **101**: 2706-2712.

Sahlström, L., 2003. A review of survival of pathogenic bacteria in organic waste used in biogas plants. *Bioresource Technology*, **87**: 161-166.

Sawayama, S., Tada, C., Tsukahara, K. and T. Yagishita, 2004. Effect of ammonium addition on methanogenic community in a fluidized bed anaerobic digestion. *Journal of Bioscience and Bioengineering*, **97**: 65-70.

Schievano, A., D'Imporzano, G. and F. Adani, 2009. Substituting energy crops with organic wastes and agro-industrial residues for biogas production. *Journal of Environmental Management*, **90**: 2537-2541.

Schmid, J., Krautkremer, B. and J. Müller, 2005. Biogas-powered microgas-turbine. *Proceedings Expo World Conference on Wind Energy, Renewable Energy and Fuel Cells, Hamamatsu/Japan*, 7.

Schneider, R., Quicker, P., Anzer, T., Prechtl, S. and M. Faulstich, 2002. Grundlegende Untersuchungen zur effektiven, kostengünstigen Entfernung von Schwefelwasserstoff aus Biogas. In: *Biogasanlagen Anforderungen zur Luftreinhaltung, Bayerisches Landesamt für Umweltschutz, Augsburg.*

Schulte-Schulze Berndt, A., 2005. Biogas upgrading with pressure swing adsorption versus biogas reforming. In: *Lens P, Westermann P, Haberbauer M, Moreno A (eds) Biofuels for fuel cells,* pp. 414-429.

Schulz, H. and B. Eder, 2001. Biogas-Praxis. Grundlagen - Planung - Anlagenbau. Ökobuchverlag, Staufen bei Freiburg.

Strauch, D. and W. Philipp, 2000. Hygieneaspekte der biologischen Abfallbehandlung und -verwertung. In: Bidlingmaier W (Editor), *Biologische Abfallbehandlung.* Eugen Ulmer, Stuttgart, pp. 155-208.

Su, H., Cheng, J., Zhou, J., Song, W. and K. Cen, 2009. Improving hydrogen production from cassava starch by combination of dark and photo fermentation. *International Journal of Hydrogen Energy*, **34**: 1780-1786.

Tanaka, S., Kobayashi, T., Kamiyama, K. and M. Bildan, 1997. Effects of thermochemical pretreatment on the anaerobic digestion of waste activated sludge. *Water Science and Technology*, **35**: 209-215.

Tani, M., Sakamoto, N., Kishimoto, T. and K. Umetsu, 2006. Utilization of anaerobically digested slurry combined with other waste following application to agricultural land. In: *International Congress Series*. **1293**: 331-334.

Themelis, N. J. and P. A. Ulloa, 2007. Methane generation in landfills. *Renewable Energy*, **32**: 1243-1257.

Tiehm, A., Nickel, K., Zellhorn, M. and U. Neis, 2001. Ultrasonic waste activated sludge disintegration for improving anaerobic stabilization. *Water Research*, **35**: 2003-2009.

Trzcinski, A. P., Ray, M. J. and D. C. Stuckey, 2010. Performance of a three-stage membrane bioprocess treating the organic fraction of municipal solid waste and evolution of its archaeal and bacterial ecology. *Bioresource Technology*, **101**: 1652-1661.

Umetsu, K., Yamazaki, S., Kishimoto, T., Takahashi, J., Shibata, Y., Zhang, C., Misaki, T., Hamamoto, O., Ihara, I. and M. Komiyama, 2006. Anaerobic co-digestion of dairy manure and sugar beets. *International Congress Series*. **1293**: 307-310.

Ward, A. J., Hobbs, P. J., Holliman, P. J. and D. L. Jones, 2008. Optimisation of the anaerobic digestion of agricultural resources. *Bioresource Technology*, **99**: 7928-7940.

Weiland, P., 2003. Production and energetic use of biogas from energy crops and wastes in Germany. *Applied Biochemistry and Biotechnology*, **109**: 263-274.

Weiland, P., 2006. State of the art of solid-state digestion–recent developments. In: F.N. Rohstoffe, (Editor), *Solid-State Digestion–State of the Art and Further RandD Requirements*, Volume 24, Gulzower Fachgespräche, pp. 22-38.

Weiland, P., 2010. Biogas production: current state and perspectives. *Applied Microbiology and Biotechnology*, **85**: 849-860.

Weiland, P., Verstraete, W., and A. Van Haandel, 2009. Biomass digestion to methane in agriculture: A successful pathway for the energy production and waste treatment worldwide. In: W. Soetaert, E.J. Vandamme (Editors), *Biofuels*, Wiley, pp. 171-195.

Xing, W., Ngo, H.H., Guo, W., Wu, Z., Nguyen, T.T., Cullum, P., Listowski, A. and N. Yang, 2010. Enhancement of the performance of anaerobic fluidized bed bioreactors (AFBBRs) by a new starch based flocculant. *Separation and Purification Technology*, **72**: 140-146.

Yan, J. Q., Lo K. V. and P. H. Liao, 1989. Anaerobic digestion of cheese whey using up-flow anaerobic sludge blanket reactor. *Biological Wastes*, **27**: 289-305.

Yang, S. T. and M. R. Okos, 1987. Kinetic study and mathematical modeling of methanogenesis of acetate using pure cultures of methanogens. *Biotechnology and Bioengineering*, **30**: 661-667.

Zhang, R., El-Mashad, H. M., Hartman, K., Wang, F., Liu, G., Choate, C. and P. Gamble, 2007. Characterization of food waste as feedstock for anaerobic digestion. *Bioresource Technology*, **98**: 929-935.

Zhao, Y., Wang, A. and N. Ren, 2010. Effect of carbon sources on sulfidogenic bacterial communities during the starting-up of acidogenic sulfate-reducing bioreactors. *Bioresource Technology*, **101**: 2952-2959.

Zhu, B., Gikas, P., Zhang, R., Lord, J., Jenkins, B. and X. Li, 2009. Characteristics and biogas production potential of municipal solid wastes pretreated with a rotary drum reactor. *Bioresource Technology*, **100**: 1122-1129.

Received June, 2, 2012; accepted for printing December, 2, 2012.