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Production of Biogas from Sludge Waste and Organic Fraction of Municipal Solid Waste

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1. Introduction

The pollution of water, air and soil by municipal, industrial and agricultural wastes is a major concern of public autorithies who imperatively have to encourage the development of effective and non expensive treatment technologies. Although it is not recent, the process based on the anaerobic digestion (bio-methanisation) for the treatment of the waste organic fraction, is getting very attractive from the environmental and the economical points of view. It consists of a biological degradation of the organic matter, under anaerobic conditions, where a biogas, mainly methane (CH_4) is evolved, and hence providing a renewable source of energy which may be used in the production of electricity and heat.

Generally various types of residual sludges and solid wastes are generated by human activities. They are composed of organic matter which may or may not be easily biodegradeable, inorganic matter, inert soluble and non soluble matter, toxic matter, etc. In order to treat these solid wastes, it is first required to characterise them and second to choose a treatment mode depending on their types and their possible final destinations. According to the physical state, one may distinguish solid wastes (dehydrated sludges, domestic wastes, etc.), liquid wastes (effluents from food, fresh liquid sludges, etc.) and suspensions (sludges from water treatment plant). Classification in terms of the sources may be as follows:

- Biomass and organic wastes: these are potential biodegrable materials since they are made of natural organic molecules which may be inserted into the biogeochemical of the matter, particularly the carbone cycle. Industrial wastes can be concerned since they have non negligeable organic matter concentrations.
- Agriculture and food wastes such as manure and other wastes from breeding. The treatment of these wastes in treatment plants generate sludges rich in organic matter and hence are potentially biodegradable , requiring adapted methods.
- Municipal wastes which include domestic wastes and other types depending on the mode and nature of the collection: from small and moderate industrial units, public spaces, etc. They represent a good fraction of fermentable ready to undergo a biological treatment.
- Sludges from municipal wastewaters treatment plants: these are the main wastes produced by a treatment plant and are mainly constitued of dead bacteria and

mineralised organic matter. The sludge characterisation is essential for the choice of the most adequate treatment method as well as for the prediction of each treatment stage performance. Generally distinction is made between primary sludges which are recovered by simple waste waters decantation, and are of high concentrations in mineral and organic matter, and the biological or secondary sludges resulting from a biological treatment of waters. These latter have different compositions, depending on the nature of the degraded substrate, the operation load of the biological reactor and the eventual stabilising treatment.

For the treatment of the different pollution types, vvarious techniques and processes of different chemical, biological and physico-chemical natures as well as a coupling of the last two, are developed. The treatment and the final elimination consist of a sequence of unit operations with a great number of possible options among which the best one is to be chosen, taking into account the upstream (nature, characteristics, and waste quantities) and downstream (local possibilities of final eliminations) constraints as well as the cost.

The present study is more concerned by the biodegradable organic solid wastes which are characterised by a high organic matter concentration, recommanding a biological treatment.

One of technologies to carry out the treatment of the organic fraction of this organic waste is anaerobic digestion (bio-methanization, this process is presented with more details in the next sections of this chapter), which consists of a biological degradation in an anaerobic phase of the organic matter into biogas with a high methane percentage. This technology is becoming essential in the reduction of organic waste volume and the production of biogas, a renewable source of energy. It can be used in a variety of ways, with a heating value of approximately 600 -800 Btu/ft and a quality that can be used to generate electricity, used as fuel for a boiler, space heater, for refrigeration equipment, or as a cooking and lighting fuel.

2. Anaerobic digestion process

2.1 Anaerobic digestion historical

The use of anaerobic digestion for the treatment and the stabilization of solid waste is not new. It had been used in the 19th century. In rural parts of China and India, simple reactor constructions were used a long time ago to treat the manure and agricultural wastes in order to recover energy for cooking and lighting (Gijzen, 2002). In 1860s in France (McCarty, 2001), the anaerobic digestion of sludge waste was obtained from wastewater treatment plant, on a large scale, by means of an advanced technology. Furthermore, at the end of 1980s, co-digestion processes treating a mixture of different types of waste, were introduced (Ahring, 2003). Today, anaerobic digestion is one of the most environmentally friendly and suitable treatment methods for of solid organic waste. This technology is widely applied for bio-energy production, because of the increasing request for renewable energy. A consequence of the increasing implementation of this technology is the necessity to determine the ultimate biogas potential for several solid substrates (Angelidaki & al., 20096).

2.2 Anaerobic digestion principle

Among the various techniques of stabilization, anaerobic digestion, or methanisation, is the most interesting one. Indeed, according to Suh and Roussaux (Suh & Roussaux, 2002), it is the least aggressive treatment, towards to the environment. The anaerobic micro-organisms use organic pollution (biodegradable organic matter) as substrate to produce biogas which can be exploited according to several forms. Thus, anaerobic digestion allows a reduction of the dry matter from approximately 50% (OTV, 1997) and the production of a biogas, mainly methane (55-70%) and carbon dioxide (25-40%), with traces of hydrogen and of H_2S, (Mata-Alvares, 2003). Methane can be developed in the form of energy (boiler producing of heat or electricity). At the same time the anaerobic micro-organisms consume little energy, which involves a limited production of muds limited (3 to 20 times lower than an aerobic treatment), (Bitton, 1994). Indeed, the micro-organisms use only approximately 10 to 15 % of the energy of the substrate for their growth (Trably, 2002 and Moletta, 1993), the remaining being used for the production of biogas. Finally, anaerobic digestion allows a reduction of the pathogenic micro-organisms.

Anaerobic digestion consists of sludge fermentation, under strict anaerobic conditions. It is made up of four stages: hydrolysis, acidogenesis, acetogenesis and the methanogenesis. To achieve an anaerobic digestion, it is necessary that the reaction kinetics for the consumed or produced component is balanced. The general diagram of anaerobic digestion is presented on Figure 1 (Edeline, 1997).

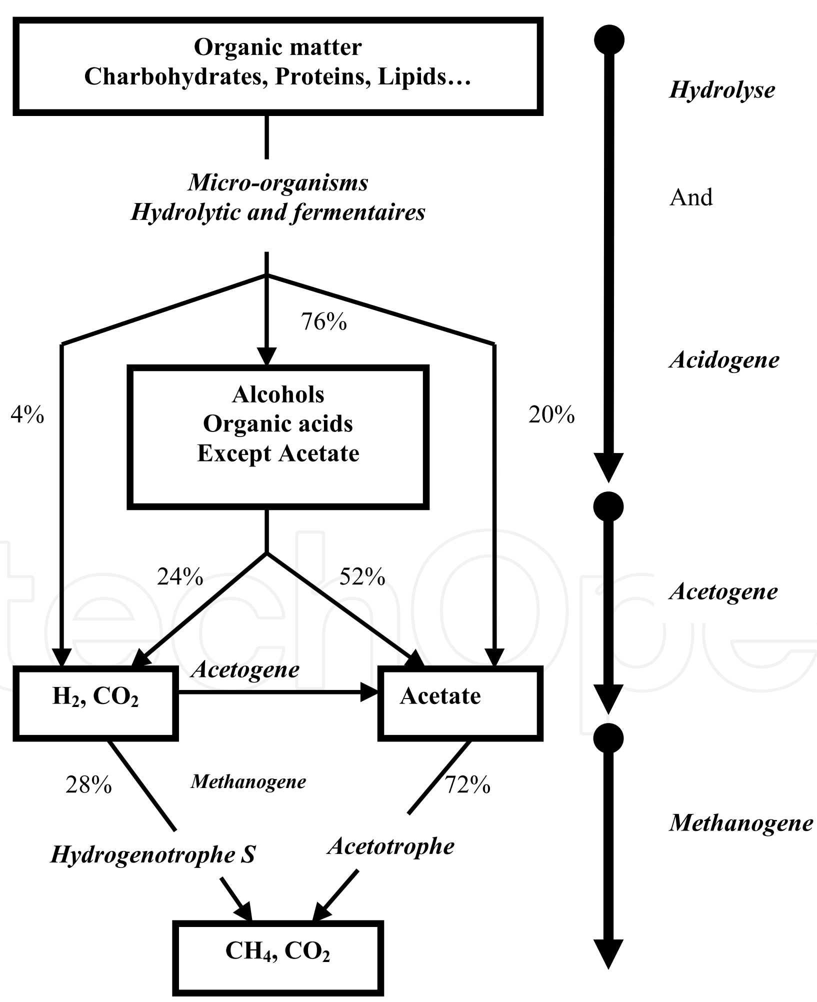

Fig. 1. Diagram of trophic chain of the methanogene and its various stages (Edeline, 1997)

2.3 Anaerobic digestion steps

Anaerobic digestion is a biological process, which is used for the treatment and valorisation of organic waste. Generally It goes through the four steps, as mentionned above, and which are hydrolysis, acidogenesis, acetogenesis and methanogenesis. In the case of co-digestion biodegradable solid waste is added at the head of the process. A preliminary stage of disintegration of the substrate, which is in general a nonbiological step for the transformation of the complex polysaccharide, lipids and proteins, is considered (Thiele, 1991).

2.3.1 Hydrolysis

The hydrolysis is an extracellular process in which complex particulate organic substances (proteins, polysaccharides, lipids, cellulose… etc) are broken up into simple soluble compounds (acid amino, simple, acid sugars fatty, glycérol… etc). It is a significant stage before the process of fermentation, because the fermentative bacteria cannot absorb complex organic polymers directly in their cells. The hydrolytic enzymes include the cellulase, the cellobiase, the xylanase and amylase for the decomposition of sugar polysaccharides, the protease for the degradation of the protein in amino acids, and lipase for the degradation of the glycerol lipids and the fatty acids with long chain (LCFA) (Batstone & al., 2002 and Kaseng & al., 1992).

2.3.2 Acidogenesis

The acidogenic step consists of a degradation of produced components from the hydrolysis step, by the action of acidogenic and fermentative bacteria. It leads to the formation of a mixture of: organic acids, volatile fatty acid (VFA), alcohols, hydrogen, carbon dioxide, ammonium, etc.

Examples of the various products of the fermentation of glucose are shown in the following Table 1:

Products	Reactions
Acetate	$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$
Propionate + Acetate	$3C_6H_{12}O_6 \rightarrow 4CH_3CH_2COOH + 2CH_3COOH + 2CO_2 + 2H_2O$
Butyrate	$C_6H_{12}O_6 \rightarrow CH_3CH_2CH_2COOH + 2CO_2 + 2H_2$
Lactate	$C_6H_{12}O_6 \rightarrow 2CH_3CHOHCOOH$
Ethanol	$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$

Table 1. Exemples de la fermentation du glucose (Dolfing, 1988; Angelidaki & Ellegaard, 2002 ; Rodriguez, 2006)

The dominant route depends on several factors such as the concentration in substrate, pH and hydrogen concentration (Balk et al., 2002). Under a very high organic load, the lactic acid production becomes significant (Mattiasson, 2004). With low pH (lower than 5) the production of ethanol is high, whereas with lower pH (lower than 4) there is a strong production of the volatile fatty acids (VFA) (Ren & al., 1997).

However, the partial hydrogen pressure has a great influence on the fermentation route where a low value encourages the fermentation to acetate and hydrogen is favoured (Thauer, 1977).

2.3.3 Acetogenesis

The acetogenic step allows the transformation of the acids, resulting from acidonenic step to acetate, and carbon dioxide, by the action of the acetogenic bacteria. This operation is carried out by different types of bacteria.

2.3.4 Methanogenesis

The mehanogenic step consists of the transformation of acetate, hydrogen and carbon dioxide into methane. For that, there are two main system routes:

1. Aceticlastic methanogens : acetate + $H_2 \Leftrightarrow CO_2 + CH_4$
2. Hydrogenotrophic methanogens: $CO_2 + 4\ H_2 \Leftrightarrow 2\ H_2O + CH_4$

There are other minor routes which have a low importance. In the anaerobic digesters, approximately 60 to 70% of methane are produced by the Aceticlastic methanogens routes (Oles, 1997).

The growth of methanogens bacteria is slow: 3 days in 35°C (Schink, 1997). As they are the most sensitive micro-organisms of the ecosystem, they govern the total kenetics of the process (Ramsay & Pullammanappallil, 2001). Moreover, they are sensitive to the presence of inhibitors such as VFA.

During the methanogenic phase, the products of fermentation such as acetate and H_2 / CO_2 are converted into CH_4 and CO_2 by methanogenic bacteria. Methanogenes bacteria can grow directly on H_2 / CO_2, acetate and all other compounds with only one carbon such as formate, methanol and the methylamine (Puñal & al., 2003).

The methanogenic step is influenced by the operating conditions of the digester, such as temperature, hydraulic loading rate, organic loading rate, and the influent substrate composition (McHugh & al., 2003).

3. Types of digesters and applications

The conventional anaerobic digesters operate as semi continuous, continuous or closed. The operations in semi continuous or continuous are preferable because the maximum growth rate can be obtained by controlling the effluent rate. In the closed system, a balance cannot be obtained while the concentrations of the components in the digester change with time (Karakashev & al., 2005).

The choice of the type of digester used is related to treated waste characteristics. Solid waste and sludge are mainly treated in digester with continuous flow (CSTRs), whereas soluble organic waste is treated by a use of biofilm systems such as the anaerobic filters and fluidized bed digesters with ascending flow (UASB) Smith & al., 2005).

In the systems of biofilm the biomass is maintained in the aggregates of the biofilm/granule where the solid retention time (SRT) is much higher than the hydraulic retention time

(HRT). The advantage is that the digester can operate with a high flow and can tolerate higher concentrations of toxic species than in (CSTR) systems. The biofilm system operates normally in a continuous mode with an (HRT) lower than 5 days. The systems can operate in a wide range of temperature and psychrophils conditions (3°C) up to the extra-thermophiles conditions (80°C). For the anaerobic treatment of soluble organic waste the systems of UASB at high rate are used.

In CSTR systems, the biomass is suspended in the main liquid and will be removed as well as the effluent so that the solid retention time (SRT) is equal to the hydraulic retention time (HRT). This makes it necessary to operate at a high hydraulic retention time (HRT) , between 10 and 20 days, to avoid the scrubbing of the methanogens which have a long time of growth.

4. Factors affecting the anaerobic digestion process stability

The factors affecting the production of biogas are mainly based on the operating conditions of the digester, such as pH and temperature which influence directly the micro-organisms. The perturbations in effluent (including the concentration of substrate and its composition in toxic compounds and inhibitors) can also affect the volume and the quality of the produced biogas. Sometimes, the toxic compounds are not present at the beginning in the effluent waste, but they are produced inside the digester starting from degradation of substrate (example: VFA and ammonia).

4.1 Substrate

The type and the composition of the substrate determine directly the quality of the produced biogas. In anaerobic process the substrate is often measured in term of chemical oxygen demand (COD) or of total volatile solids (TVS). It is significant to distinguish between the degradable and the inert fraction, because a considerable fraction of the COD in effluent is inert (Nielsen, 2006). The waste which contains a high percentage of water has a weak methane yield by COD or VS.

Organic waste contains various compounds: mainly saccharides (which are divided into two fractions, easily and slowly degradables), lipids (easily degradable), proteins (easily degradable), VFA (easily degradable), as well as others compounds (Moosbrugger & al., 1993). The production of methane is generally in the range from 100 to 400 L CH_4 / kg VS.

On the other hand, the majority of organic waste contain a high fraction of the substrate easily degradable, which gives a high production of methane and VFA. It is thus significant to control the organic and hydraulic loading according to the capacity of the digester when the process functions are at low charge that gives also a low production rate of biogas. Although this can prevent the rupture of the process, it is not very ecomical because the capacity of the process is not completly used. The increase in the charge gives more biogas but also there is the risk of the overload, with, as a consequence, the accumulation of the VFA. The high concentration of VFA decreases the pH and making them more toxic for methanogens bacteria.

Sufficient nutriments are also impotant for microbial growth. The macro nutriments such as carbon, hydrogen, nitrogen and oxygen are the main components of the cells in the biomass, with others like sulphur, the phosphorus, the potassium, the calcium, the magnesium and the iron which are required (McMahon & al., 2001). The majority of the nutriments can be inhibiting if they are present at high concentrations.

4.2 Temperature

Anaerobic digestion can be applied in a wide range of temperature, into psychrophilous (< 20 °C) (Vavilin & Angelidaki, 2005), in mesophile (25-40 °C), thermophile (45-60 °C) (Angelidaki & al., 2005), and even in extra thermophile conditions (> 60 °C) (Liu, 2003). The temperature has a direct effect on the physicochemical properties of all the components in the digester and affects also the thermodynamics and the kinetics of the biological processes. The temperature determines if a specific reaction is favorable.

The increase in the temperature has the following advantages:

1. Increase the solubility of the organic compounds which makes them more accessible to the micro-organisms.
2. Increase the chemical and Biological reaction rates and hence accelerates the conversion process, therefore the reactor can be smaller and can operate with a shorter hydraulic retention time (HRT)
3. Improve several physicochemical properties like diffusivity of the soluble substrate, the increase in the rate of transfer of liquid towards gas due to the low solubility of the gas, reduction in the liquid viscosity which makes decreased the energy of agitation necessary and also improves separation liquid-solid separation of the biomass.
4. Particularly increase the death rate of the pathogenic bacteria, which decreases necessary time for the reduction of pathogenic bacteria (Hansson, 2002).
5. Moreover, the reactions of oxidations of organic acid become more energetic at high temperature, which is advantageous for the degradation of fatty acid to long chain fatty acid, and other intermediaries (Chynoweth & al., 1994). Nevertheless, the high temperature can have a certain negative effect. The increase in the temperature decreases the pKa of ammonia, thus increasing the free fraction of ammonia (NH_3) which is an inhibitor of the micro-organisms. Moreover, the rise in the temperature increases the pKa of VFA, which increases its not dissociated fraction, particularly with low pH (4-5), as in the acidogenic reactor (Chynoweth & al., 1994). This makes the thermophilic process more sensitive to inhibition. However, because of the multiplicity of advantages at high temperatures, the thermophilic operation is popular in the anaerobic applications where the ammonia inhibition is not the first consideration.

4.3 pH and buffer value

The level of pH has an effect on the enzymatic activity in the micro-organisms, since each enzyme is in activity only in one specific range of pH, and it has its maximum activity with its optimal pH (Ahring, 1994). A stable pH indicates system equilibrium and digester stability. A falling pH decrease can point toward acid accumulation and digester instability. Gas production is the only parameter that shows digester instability faster than pH. The range of acceptable pH for the bacteria participating in digestion is from 5.5 to 8.5, though the closer to neutral, the greater the chance that the methanogenic bacteria will function

(Golueke, 2002). Most methanogens function in a pH range between 6.7 and 7.4, and optimally between 7.0 and 7.2. The greatest potential for a digester failure is a result of acid accumulation. This would occur if the amount of volatile solids loaded into the digester as fresh waste increased sharply. Maintaining pH is especially delicate in the start-up because fresh waste must undergo acid forming stages before any methane forming can begin, which will lower the pH. To raise the pH during the early stages, operators must add a buffer to the system, such as calcium carbonate or lime.

4.4 Intensity of mixture

Several studies proved that the intensity of mixture in an CSTR digester has an effect on the process inhibition and the re-establishment of the organic overload (Hill & Bolte, 1989). Other researchers (Hill, 1990) studied the accumulation of acetate and propionate in a CSTR digester which treats municipal solid waste and the biosolides with an aggressive starting and an organic overload. They noted that while acetate was consumed thereafter, propionate persisted in the whole system and it started to decrease only after the reducing of mixture intensity. They also noted that a digester with a reduced mixture can tolerate a higher organic load than the digester with an intensive mixture.

4.5 Composed toxic/inhibiting

The inhibiting compounds are one or the other present already in the substrate or product during degradation. The majority of the inhibitors are formed during the degradation of the substrate, such as VFA, LCVA, ammonia and sulphide. Some inhibitors are present already in substrate, such as the heavy LCVA, and metals.

The VFA is the main intermediate in anaerobic digestion, and it accumulates under the action of the non balance of the process. With low pH, the VFA becomes more toxic, due to the increase of the non dissociated fraction.

Ammonia comes mainly from the degradation of protein. A study on 18 central biogas stations in Denmark, proved that ammonia was significatif factor affecting the stability of the process (Hawkes & al., 1994). A concentration about 2 gN/l of ammonia will have no inhibiting effect on acetoclastic methanogens (Hill & Holmberg, 1988). However, the activity of methanogens is decreased during the increase in ammonia concentration, and total inhibition is reached for a concentration of 10 gN/l.

5. Control parameters of the process of biogas

The control of the anaerobic digesters is necessary to ensure a good operating of the digester. Since anaerobic digestion is a complex process implying several groups of micro-organisms which are sensitive to several factors of operation, it is significant to be able to detect the non balance of the process at the beginning to take an action in time to prevent its failure. As with other biological processes, anaerobic digestion can be controlled by measuring the substrate convertion (COD or removed VS), the accumulation of intermediaries (VFA, pH, alkalinity, H_2, CO), the formation of product (gas production rate, CH_4, CO_2).

5.1 Methane and carbon dioxide

Biogas is composed mainly of CH_4 and CO_2. The ratio CH_4 to CO_2 is normally stable in the digester and any change may be due to the process instability. However, the ratio also depends on the composition of the substrate, the temperature, the pH and the pressure (Hickey & Switzenbaum, 1991). Since the dissolution of CO_2 strongly depends on the pH, the fluctuation of the pH can also change the gas composition. A better indicator is thus the production of methane, rather than its composition in the gas (Anderson & Yang, 1992).

The production of methane combines the production of biogas with the measurement of percentage of methane. The production rate of methane (L-CH_4/days) was used successfully like an on line indicator to control a CSTR digester (Feitkenhauer & al., 2002).

5.2 PH

The pH is relatively easy to measure, and is often the only parameter of the liquid phase which is measured on line. The change of the pH can be an indicator, for the stability of anerobic digestion process. Since the micro-organisms can grow at only one specific pH range. The effluent pH can also affect the pH in the digester. The use of the pH as an indicator is normally based on the fact that a decrease of the pH corresponds to the accumulation of VFA. Some anaerobic systems apply the control of the pH where an acid or a base is added to ensure the suitable pH for the microbial growth.

5.3 Alkalinity

Alkalinity is a better alternative than the pH to indicate the accumulation of VFA, because the increase in VFA will directly consume alkalinity before the great change of pH. However, it is proved that the total alkalinity (TA) measured by the titration of the sample with pH 4.3 is not very sensitive because of the combination of result of VFA and bicarbonate to the TA (Hill & Bolte, 1989). Partial Alkalinity (PA) or bicarbonate alkalinity measured by titration of sample in pH 5.75 has an empirical correlation to the VFA accumulation (Wang & al., 2005). However, one does not observe this during the VFA accumulation at the time of the ammonia overload, because this latter increases the alkalinity of the system (Wang & al., 2005).

5.4 Volatile fatty acids

The accumulation of the volatile fatty acids (VFA) during the non balance of the process reflects directly an uncoupling kinetic between the acid producers and consumers (Hickey & al., 1989). The concentration of VFA was suggested for the control and the monitoring of the anaerobic digester (Hill & Bolte, 1989). The VFA is generally measured by gas chromatography (GC) with the use of a detector with ionization of flame (FID), to obtain the individual VFA, or by titration which gives the concentration of total VFA, and which is less expensive and is largely used at the commercial biogas plants. Several methods of titration for the determination of total VFA were proposed, for example a simple titration (Delbès, 2000), a titration at 5-point, and a titration at 8-point.

However, several studies specified that the individual VFA can provide more significant information concerning an early failure of the process the failure of process (Nielsen, 2006).

5.5 Organic matter reduction

There are many industrial applications in which the principal goal of anaerobic digestion is the organic treatment of waste instead of the production of gas. On this subject, the elimination of the difference between the organic matter contained before and after treatment, is a significant parameter that it is necessary to control. This is measured in term of Total solid (TS), volatile solid (VS), total organic carbon (TOC), COD or BOD (Boe & al., 2005). These parameters are appropriate for the control of the anaerobic digestion applied to several types of waste.

5.6 Carbon monoxide

The carbon monoxide is a possible intermediate in the metabolic route of the acetogens and the methanogens (Moletta, 1993); Carbon monoxide was found in a great quantity during toxic inhibition by heavy metals (Liu & al., 2003). According to Moletta (Moletta, 2002) the presence of carbon monoxide is directly related to the acetate concentration, and conversely related to that of methane (Batstone & al., 2002).

N.B: there are other process control parameters of the production of biogas during anaerobic digestion, but they do not find any wide application in practice. However, the hydrogen gas is controlled in the gas phase and its measure in the liquid phase enables the identification of the existing different types of bacterial populations which may influence the process of the anaerobic digestion.

6. Physicochemical conditions necessary to anaerobic digestion

The anaerobic digestion can be carried out only under the following conditions:

- absence of oxygen, nitrates or sulphates (Degrémont, 2004).
- pH close to neutrality: optimum 6,8 – 7,5 (Moletta, 2002)
- concentration in volatile fatty acid (VFA) lower than 2 – 3 g/l (McCarty, 2001).
- a partial hydrogen pressure: 10 – 20 Pa to the maximum (Trably, 2002)
- a potential of oxydoreduction lower than -300 mV (Suh & Roussaux, 2002)
- absence of inhibiting elements: agent chlorinated, antibiotic,…
- an optimal stable temperature for micro-organisms (Bitton, 1994)

7. Advantages and disadvantages of anaerobic digestion

The advantages of anaerobic digestion are:

- A reduction of about 50% of the dry waste;
- A production of a Biogas which may undergo beneficiation in the form of energy (heating, cogeneration of electricity);
- A reduction of the number of pathogenic micro-organisms;
- An agronomic interest, related to a significant phosphate and ammoniacal nitrogen concentration (NH_4^+ (PO_4^{3}) due to the lysis of the organic matter (Münch & Greenfield, 1998);
- Request lower energy compared with aerobic processes ;
- the possibility of treating high organic loads: from 2 to more than 80 kg of COD per cubic meter of digester and per days, with a treatment rate from 80 to 98%

However, it has also certain disadvantages:

- High sensitivity to the toxic compounds (Schnurer & al., 1999);
- A slower degradation compared with aerobic processes (Bitton, 1994);
- Significant capital costs ;
- The growth kinetics of bacteria is low, the pretraitement kinetics is also low and the time needed for the treatment is relatively long;
- the microbial populations are sensitive to the disturbances, in particular with oxygen and with heavy metals (OTV, 1997);
- the treatment by anaerobic digestion is often insufficient to directly reject the effluents in the natural environment: an aerobic postprocessing is necessary to complete the elimination of carbon and possibly nitrogen and phosphorus.

8. Effect of temperature and substrate composition on biogas production

As mentioned previously, the temperature and substrate compostion have a high effect on biogas production. Their effects are confirmed by the study published by several researchers. As an example the results, obtained by Derbal et al. (Derbal & al., 2011) can be cited.

The obtained values of different parameters of the (co)-digestion experiments under mesophilic and thermophilic conditions are presented (see figure 2, 3, 4, 5, 6). It should be noted that the volume of the mesophilic co-digester which is 2000 m^3 is 20 times larger than pilot scale digesters 500 l. Therefore, the absolute biogas volume produced is different from the other cases and no comparison can be made. However, a comparison for different parameters is presented as follows:

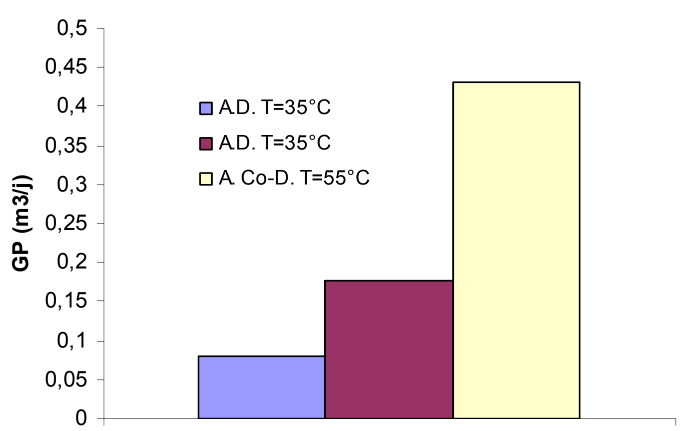

Fig. 2. Comparison of gas production (GP)

Figure 2 represents daily average biogas production values for the four studied cases where the thermophilic co-digestion shows the best results. Eventhough temperature has a certain effect on biogas production, adding solid waste is a contributing factor to this production. In fact, solid wastes contain a high percentage of organic matter.

The use of gas production rate GPR as a comparison parameter led us to include the data from the industrial scale digester. The results shown on Figure 3 confirm that the combined effect of temperature and solid waste addition is positive and considerable. Moreover, thermophilic co-digestion presents the best GPR results wich are confirmed by values of

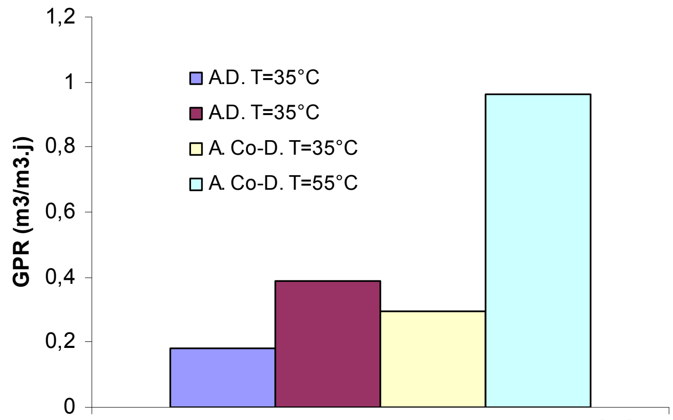

Fig. 3. Comparison of gas production rate (GPR)

SGP of Figure 4. SGP is in relation with the biodegradability of the substrate and with anaerobic process reaction. SGP increased from 0.14 to 0.33 for digestion of wastewater sludge alone when temperature increased from mesophilic conditions (35°C) to thermophilic ones (55°C), whereas for a wastewater sludge mixed with solid waste this parameter increased from 0.31 to 0.51. Adding solid waste under mesophilic comditions results in an increase of SGP from 0.14 to 0.31, whereas under thermophilic conditions SGP increased from 0.33 to 0.51. The combined effect of increasing temperature from mesophilic conditions to thermophilic ones and adding solid waste to wastewater sludge increased SGP from 0.14 to 0.51.

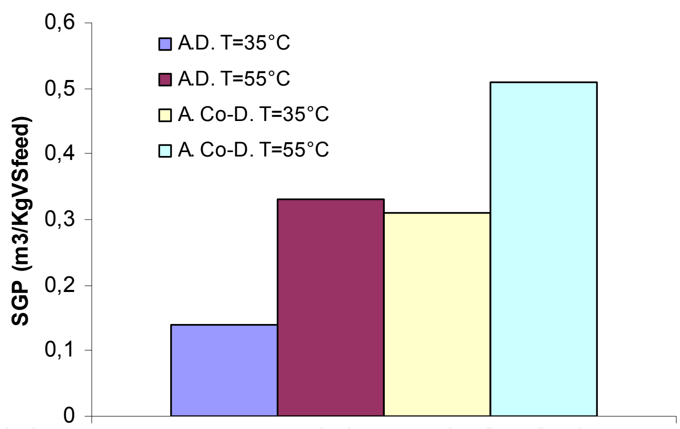

Fig. 4. Comparison of specific gas production (SGP)

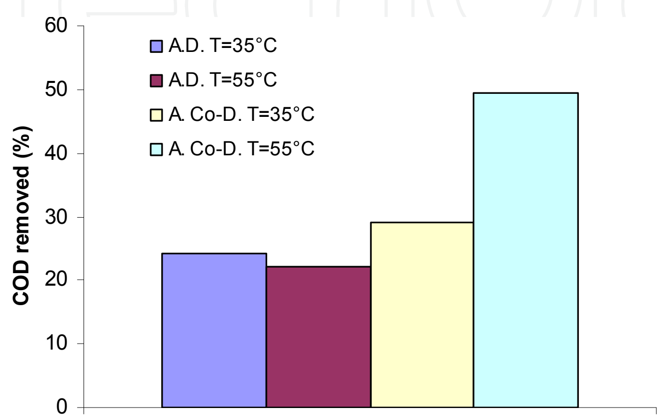

Fig. 5. Comparison of chemical oxygen demand removed (COD)

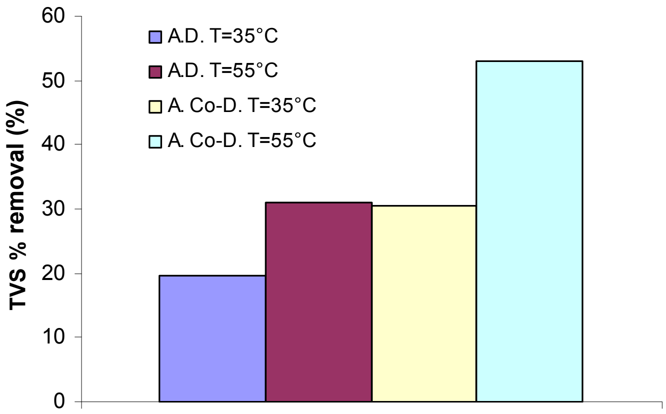

Fig. 6. Comparison of total volatile suspended removal (TVS)

Figure 5 presents the comparison of COD removal in the different studied cases. It increased from 24% for wastewater sludge alone under mesophilic conditions to 49.35% for wastewater sludge mixed with solid waste under thermophilic conditions. Moreover, for TVS thermophilic, co-digestion presents the best removal rate, 52.93%, as shown in Table 5. As a treatment system, anaerobic co-digestion under thermophilic conditions presents the best removal rates as well as specific gas production. It should be noted that changing working conditions from mesophilic to thermophilic ones increases anaerobic kinetic rates and as such the treatment capacity of a known volume will be increased as well. Adding solid waste contributes to the increase of biodegradable organic matter in the substrate (Figure 6).

As a conclusion of this sludy, the obtained results show that thermophilic co-digestion gives the best results. Although the temperature has an effect on the biogas production, it remains however quite relative compared to the effect of solid waste. These results confirm that the combined effect of the temperature and solid waste improves considerably the biogas production rate (GPR). The moving from mesophilic to thermophilic conditions, for waste sludge alone makes GPR pass from 0.18 to 0.39 m^3/m^3*d and for the waste sludge mixed with solid waste from 0.29 to 0.96 m^3/m^3*d.

The analysis of produced biogas showed that the percentage of biomethane is very high 60.37 and 64.44 for the digestion of sludge waste in mesophilic and thermophic phases, respectively and 65.8 and 60.61 for the co-digestion of solids waste with sludge waste in mesophilic and thermophilic cases, respectively.

9. Modeling of anaerobic digestion process

Due to the importance of anaerobic digestion as a treatment process, different dynamic models exist, such as the AM2 which was developed jointly by researchers of the INRA of Narbonne and the INRIA of Sophia-Antipolis in 2001 (Olivier et al., 2001). It is based on experimental results obtained on the fixed bed reactor of the INRA of Narbonne. This model is made of two steps: acidogenesis and methanogenesis corresponding to acido-acetogens and methanogens bacteria populations, respectively. As a more recent and elaborate model, the ADM1, was developed by an IWA group (Batstone et al., 2002). Its main feature is the consideration of the principal steps of anaerobic digestion process that are, respectively, substrate disintegration (non biological step), hydrolysis, acidogenesis, acetogenesis and finally the methanogenesis with seven different bacteria groups.

Since its development in 2002 and up to now, the ADM1 has been tested and used on different substrates where a great number of research works are reported in the literature. As examples, one can cite (Blumensaat and Keller, 2005) who modified the initial version of ADM1 for the simulation of a dynamic behaviour of a pilot scale digester using sludge, in order to ensure a faultless model implementation. They obtained accurate results for the cases of low to medium loading rates. However the accuracy showed a decline with the increase of the loading rate.

Wayne and Parker, 2005) considered the application of the ADM1 to a variety of anaerobic digestion configurations where the results showed, in most of the considered cases, that the model was able to reproduce the trends of the experimental results.

(Feng et al., 2006) found that the ADM1 is not sensitive to the distribution ratio of carbohydrates, proteins and lipids, whereas the fraction of short chain fatty acids (SCFA) in the influent is rather more important.

Consequently, the great capabilities of ADM1 in modelling different types of substrates and calculations have been the motivating factor to use it in the present work to evaluate the performances of a co-digestion process for the treatment of organic municipal solid waste and waste activated sludge in the above mentioned 2000 m^3 reactor working at a temperature of 37°C.

As mentioned above the ADM1 (Anaerobic Digestion Model No. 1) was developed by the IWA group (Batstone et al., 2002) with the objective to build a full mathematical model based intimately on the phenomenological model in order to simulate, at best, anaerobic reactors. It includes, as a first step, the disintegration of solid complexes (non biological step) into carbohydrates, lipids, proteins and inert material (soluble and particulate inert). The second step is the hydrolysis process of the disintegration products under an enzymatic action to produce sugars, amino acids and long chain fatty acids (LCFA), successively. Then, amino acids and sugars are fermented to produce VFA, hydrogen and carbon dioxide (acidogenesis). Then LCFA, proprionic acid, butyric acid and valeric acid are anaerobically oxided into acetate, carbon dioxide and hydrogen (acetogenesis). Finally, methane can be produced through two paths: the first one is based on acetate whereas the second one is through the reduction of carbon dioxide by molecular hydrogen. The organic species and molecular hydrogen, in this model, are expressed as COD (Chemical Oxygen Demand), whereas inorganic nitrogen and inorganic carbon species are expressed through their molecular concentrations.

Extensions and modifications were brought to ADM1 to enlarge its prediction capabilities by, taking into account other factors such as, for instance, the sulfato-reductors or the degradation of certain substrates (Wolfsberger and Halubar, 2006) and (Batstone and Keller, 2003). Moreover, Usama Zaher (Usama, 2005) considered the toxic effects of cyanide as an inhibition process for acetate.

9.1 Application of ADM1 model for simulation of organic solid waste

Concerning simulations of TCOD and SCOD, and TVFA, after estimation of substrate disintegration and hydrolysis parameters, it can be noticed that the simulated results are in good agreement with the experimental ones as shown on figure 7 and 8 respectively.

Parameters	Middle	Minimum	Maximum	Stand. Dev.	Num. samples
Sludge					
pH	7.3	6.7	7.9	0.34	36
NH_4^+ (mg N/l)	3.9	1	13	4	24
TKN (mg N/l)	43.1	31.2	49.9	8.23	16
COD (mg COD/l)	670.7	596.8	748	44.49	16
P_{tot} (mg P/g TS)	603.4	241.7	770.6	149.73	10
TS (g/l)	35.6	26.6	47.5	4.67	36
TVS (g/l)	23.1	17.2	31.1	3.05	36
TVS sludge (%ST)	64.8	58.3	80.9	4.35	36
Flow (m^3/day)	0.019	0.019	0.019	0.00	45
Waste					
TKN (mg N/l)	33.3	21.9	53.5	8.30	13
TCOD (mg COD/l)	996.2	829.7	1124.4	78.26	16
P_{tot} (mg P/g ST)	831.1	183.3	1540.9	411.99	11
TS (g/l)	160.2	72	269.9	56.42	38
TVS (g/l)	141.6	61.5	245.5	51.07	38
TVS (%TS)	89.4	73.7	94.7	4.28	38
Flow (m^3/day)	0.0032	0.0023	0.0036	0.00	45
Waste mixed with sludge					
TKN (mg N/l)	41,7	29,9	50,4	-	-
TCOD (mg COD/l)	717,6	630,3	802,2	-	-
P_{tot} (mg P/g ST)	636,2	233,3	881,5	-	-
TS (g/l)	53,5	33,1	79,5	-	-
TVS (g/l)	40,2	23,6	62,0	-	-
TVS (%TS)	68,3	60,5	82,9	-	-
Waste (m^3/day)	0.0032	0.0023	0.0036	-	-

Table 2. Influent characteristics

Parameters	Middle	Minimum	Maximum	Stand. Dev.	Num. samp
pH	7.84	7.6	8.1	0.10	44
NH_4^+ (mg N/l)	1022.1	900	1140	70	24
TKN (mg N/l)	37.8	28.7	49.1	5.45	9
TCOD(kg COD/m^3)	22.2	18.3	24.7	1.92	16
SCOD (kg COD/m^3)	4,6	2	7	2.07	5
P_{tot} (mg P/g ST)	752.2	383	1080.8	181.22	12
TS (g/l)	33.1	26.3	52.3	5.01	40
TVS (g/l)	18.9	15.5	26.8	2.18	40
TVS (% TS)	57.2	50	64.3	3.82	40
VFA (mg COD/l)	50.7	7.0	110.3	26.47	36
TA at pH 6 (mg $CaCO_3$/l)	2466.7	2181.5	2911	186.67	44
TA at pH 4 (mg $CaCO_3$/l)	4005.5	3806.4	4356	135.07	44
effluent flow (m^3/day)	0.0225	0.0225	0.0225	0.00	45

Table 3. Effluent characteristics

Parameters	Middle	Minimum	Maximum	Stand. Dev.	Num. samp
Biogas volume (m^3/day)	0.431	0.153	0.728	0.16	31
SGP (m^3 biog/kg TVS)	0.51	0.26	1.06	0.16	29
GPR (m^3 biogas/m^3 day)	0.96	0.34	1.62	0.35	31
% CH_4 (%)	60.6	55	65	2.22	40
% CO_2 (%)	39.4	35	45	2.22	40
Volume of CH_4 (m^3/day)	0.3	0.09	0.44	0.10	31
Volume of CO_2 (m^3/days)	0.17	0.06	0.28	0.06	31
H_2S (ppm)	440	200	1044	204.91	31

Table 4. Characteristics of biogas production

Kinetic parameters	Names	Units	Initial values used in ADM1	Initial values	Estimated values
$\mathbf{K_{dis}}$	Disintegration constant	Day^{-1}	0.5[b]	0.7	0.7
$\mathbf{K_{hyd.Ch}}$	Carbohydrate hydrolysis constant	Day^{-1}	10[b]	1.25[a]	1.0
$\mathbf{K_{hyd.Pr}}$	Proteins hydrolysis constant	Day^{-1}	10[b]	0.5[a]	0.7
$\mathbf{K_{hyd.Li}}$	Lipids hydrolysis constant	Day^{-1}	10[b]	0.4[a]	1.0

[a] Middle values obtained from (Mata-Alvarez , 2003)
[b] Values obtained from (Batstone and Keller, 2003)

Table 5. Initial and estimated values of kinetic parameters

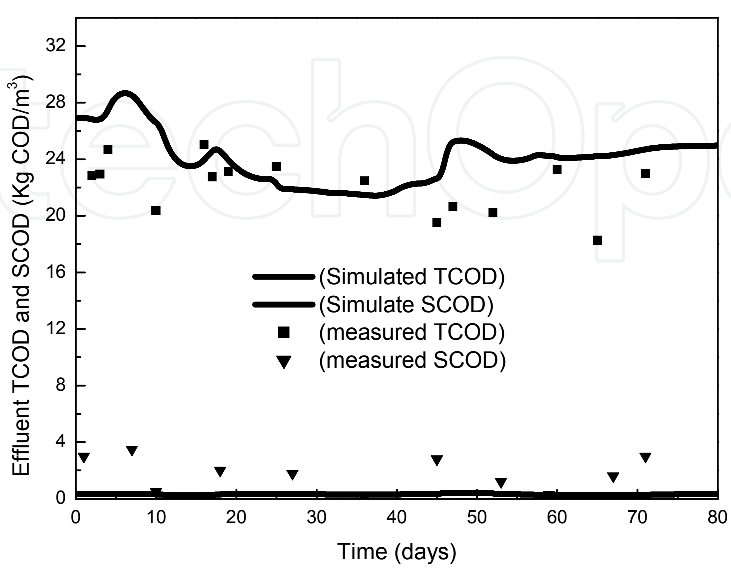

Fig. 7. Comparison between the simulation and the experimental total and souble COD

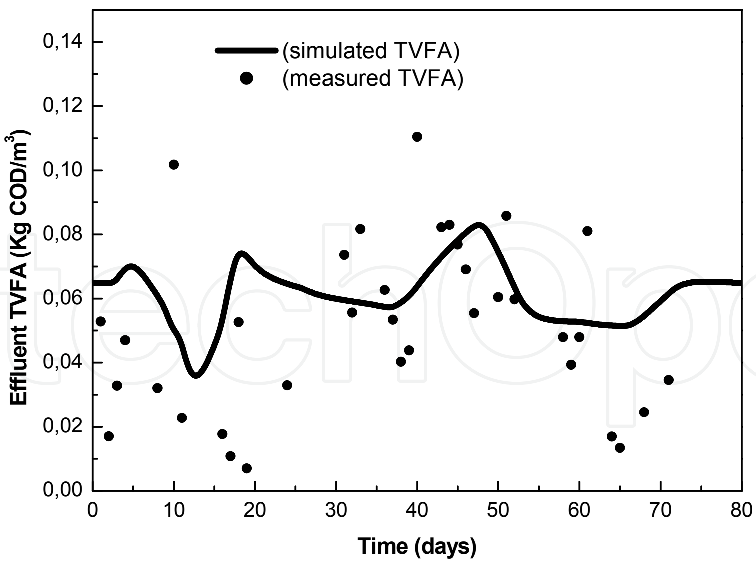

Fig. 8. Comparison between the simulation and the experimental TVFA

However the simulated results of SCOD are somehow underestimated in comparison with the experimental ones. This may be explained by the fact that the substrate distribution between proteins, carbohydrates and lipids was not measured but default model values were adopted for this parameter.

The simulated TVFA results show good digester stability and are in good agreement with the experimental ones as well.

Figure 9 shows variation of the experimental and simulated results of total biogas volume produced, which depends on the nature, the composition and the biodegradability of solids. In this case, mass loading fluctuate as shown by the ORL, it should be underlined that the main objective of these experiments was to increase the ORL to the practical limits in order to treat a maximum quantity of solid waste however it was difficult to maintain it constant. Consequently these variations condition the tendency of biogas volume produced variation. The limitations of ADM1 imply that the simulated biogas production follows an average course; therefore, the simulated data overlaps partially the experimental values.

Figure 10 shows the experimental and simulated results of biogas production. The biogas is composed principally of methane and carbon dioxide and a small percentage of hydrogen. It can be noticed that the simulated results are in good agreement with the experimental ones. A similar remark concerning the average course of the curve can be held as well. Moreover, they show a good stability in the operating of the reactor

To have a clear picture of what is happening within the system, inorganic carbon (IC) and inorganic nitrogen (IN) as well as pH, were represented on the same graph as presented in Figure 11.

Since pH is approximately equal to 8, IC represents alkalinity. Any variation in alkalinity is due to neutralisation of VFA, if accumulated. Furthermore, alkalinity or IC is more sensitive to VFA accumulation than pH and therefore more reliable.

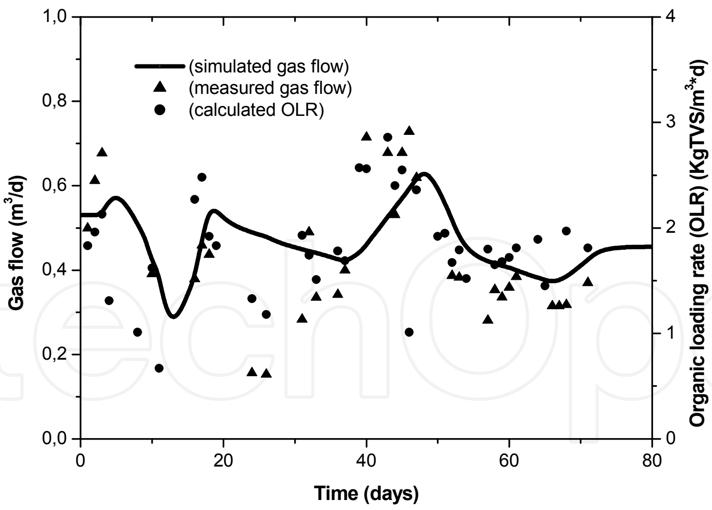

Fig. 9. Comparison between the simulation and the experimental biogas production rate and the variation of the organic loading rate (OLR) with time

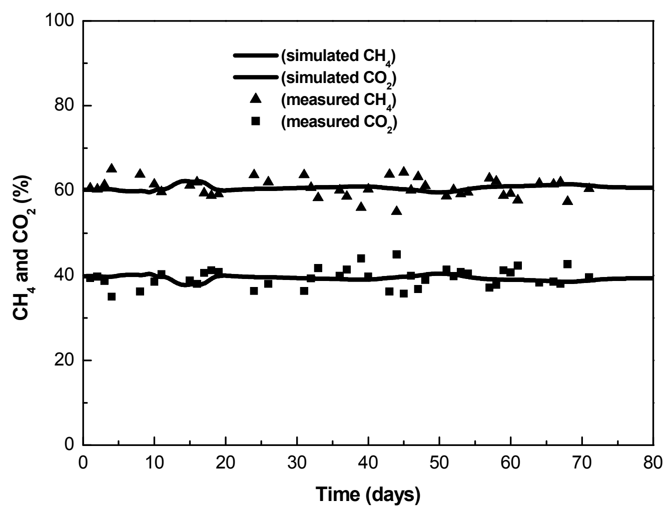

Fig. 10. Comparison between the simulation and the experimental % of CO_2 and CH_4

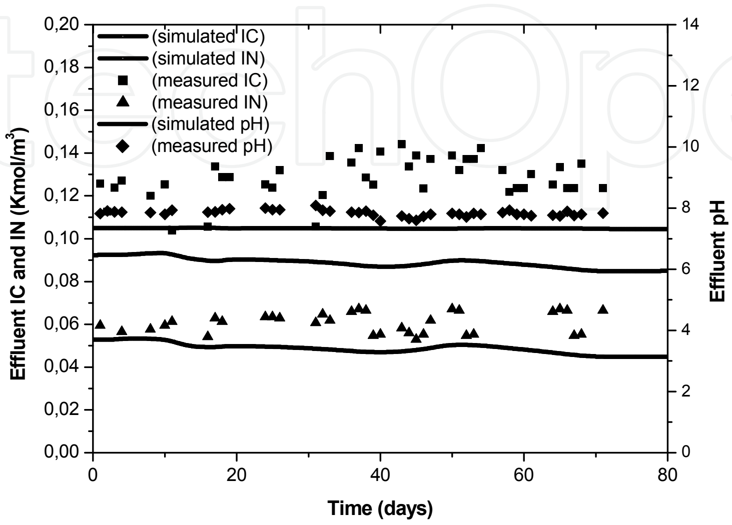

Fig. 11. Comparison between the simulation and the experimental IC, IN and pH

It is noted that in this study, the simulated results show an acceptable fit for Total chemical oxygene demand (COD), biogas volume and composition, pH and inorganic nitrogen (IN). However, for inorganic carbon (IC), the simulated results do not show a good fit. It was confirmed that IC or bicarbonate alkalinity is a very sensitive parameter to volatile fatty acids (VFA) accumulation, compared to pH variations and hence it can be used as a monitoring parameter.

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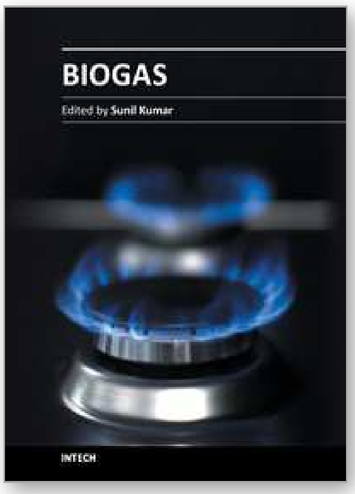

Biogas

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This book contains research on the chemistry of each step of biogas generation, along with engineering principles and practices, feasibility of biogas production in processing technologies, especially anaerobic digestion of waste and gas production system, its modeling, kinetics along with other associated aspects, utilization and purification of biogas, economy and energy issues, pipe design for biogas energy, microbiological aspects, phyto-fermentation, biogas plant constructions, assessment of ecological potential, biogas generation from sludge, rheological characterization, etc.