



ISSN 2286-4822  
[www.euacademic.org](http://www.euacademic.org)

EUROPEAN ACADEMIC RESEARCH  
Vol. IV, Issue 10/ January 2017

Impact Factor: 3.4546 (UIF)  
DRJI Value: 5.9 (B+)

## Theoretical Comparison between a Traditional Anaerobic Digestion and an Innovative One

EZIO DI BERNARDO<sup>1</sup>

ASOC OVERSEAS Consulting, Frosinone, Italy

DARIO POZZETTO<sup>2</sup>

Department of Engineering and Architecture

University of Trieste, Trieste, Italy

SIMONE ROCCO<sup>3</sup>

ASOC OVERSEAS Consulting, Frosinone, Italy

### Abstract:

*The paper, after analyzing the technical characteristics of anaerobic digestion traditional plants of zootechnical effluents, identifies those relating to an innovative system, which divides the evolutionary stages of biodegradation of the material in hydrogenesis aerobic, hydrogenesis anaerobic, acidogenesis-acetogenesis and methanogenesis.*

*The theoretical treatment will have to find validation in the pilot plant which will be building and from which it will be possible to determine additional technical, economic, and environmental indications.*

---

<sup>1</sup> He is an expert and research interest on the field of Efficiency Energy and Renewable Energy Sources. Has five publications presented at National conference. Email: [ezio.dibernardo@gmail.com](mailto:ezio.dibernardo@gmail.com)

<sup>2</sup> Author of two hundred scientific paper and scientific interests oriented on waste treatment project and management, eco-efficiency in industrial plants, rational utilization of new and traditional energetic resources, emissions by industrial plants, ergonomic problems, quality systems and production management, automation of industrial process, industrial energetic recovers and saving, industrial logistic, supply chain management and life cycle assessment. Email: [pozzetto@units.it](mailto:pozzetto@units.it)

<sup>3</sup> He is an expert and research interest on the field of Efficiency Energy and Renewable Energy Sources. Has two publications presented at National conference. Email: [simone-rocco@libero.it](mailto:simone-rocco@libero.it)

**Key words:** aerobic hydrogenesis, anaerobic digestion, free energy Gibbs, sustainable energy, zootechnical effluent

## 1. INTRODUCTION

In the last decades, the continuous growth of the world's energy demand and the ability to realize localized plants of eco-sustainable generation, has led to the creation of a myriad of anaerobic digestion plants feeding with zootechnical effluents.

In the scientific literature, many studies can be found about mathematical models that simulate the anaerobic digestion of wastewaters, organic solid wastes or sludges, evaluating performance of the systems (Biernacki et al., 2013), (Blumensaat and Keller, 2005), (Cecchi et al., 2011), (Chen Z. et al., 2009), (Cheng J. et al., 2013), (Derbal et al., 2009), (Donoso-Bravo et al., 2011), (Forster et al., 2008), (Jang H.M. et al., 2014), (Lauwers et al., 2013), (Lee et al., 2009), (Mehdizadeh et al., 2012), (Momoh et al., 2013), (Muha et al., 2013), (Ramirez et al., 2009), (Seghezze et al., 1998), (Zamanzadeh et al., 2013), (Zhao et al., 2010).

Various problems, such as the low yield of methane and the instability of the process, prevent from applying anaerobic digestion on a large scale, although considerable efforts have been made to identify mechanisms of control and factors of inhibition (Chen Y. et al., 2008), (Donoso-Bravo and Mairet, 2012), (Li et al., 2011), (Yenigum and Derimel, 2013).

Current technology has reached a maturity technological-productive which is unlikely may have further developments, although we can count on research of several scholars in the characterization and monitoring of process (Alvarez and Liden, 2008), (Chen Y. et al., 2014), (Cuertos, 2008), (Dareioti, 2009), (Golkowska and Greger, 2013), (Holm-Nielsen, 2009), (Jang H.M. et al., 2013), (Lastella et al., 2002), (Liang et al., 2011), (Madsen et al., 2011), (Mata et al., 2000),

(Meabe et al., 2013), (Mudhoo and Kumar, 2013), (Muha et al., 2013), (Mumme et al., 2010), (Orozco et al., 2013), (Raposo et al., 2011), (Shigematsu et al., 2003), (Tang et al., 2008), (Vavilin et al., 2008).

The anaerobic digestion process can take place in very different operating conditions, according to the thermal conditions of the reaction (psychrophilic, mesophilic, thermophilic, hyper-thermophilic), highlighting, for each temperature range, a specific composition of the artificial ecosystems there grown.

It has therefore been decided to exploit such microbiological differentiations splitting the single or the two-stage of a traditional digester in four stages: in this way we will create specific artificial ecological niches, with different physico-chemical and microbiological characteristics, that should enable to get a better yield of biogas and a more stable process.

It is consequently interesting to make a comparison between the two plant configurations at parity of electrical power production, not only from a biological point of view, but mainly from the technical one, so as to highlight the sustainability of the proposed innovative solution.

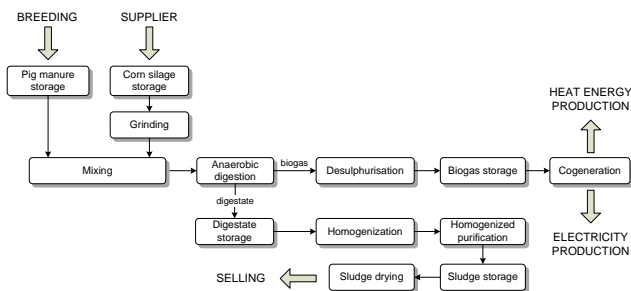
## **2. CASE STUDIES**

Below, the main stages of the two processes are considered.

### *2.1 Traditional anaerobic digestion plant*

As can be seen from the large existing literature (Hessami et al., 1996), (Korres et al., 2013), (Mudhoo, 2012), (Ozuolmez et al., 2015) the production process of a conventional anaerobic digestion plant which, in this case, has the potentiality of approximately 300 kW<sub>e</sub>, is divided into the following operational phases (see Fig. 1):

a) storage of zootechnical effluent resulting from pig farms  
 The storage consists of a cylindrical reinforced concrete tank of adequate sizes with a capacity such as to have a 24 hours material reserve of 180 m<sup>3</sup>, according to the number and size of head present in the farm, corresponding to 32.7 t/day of zootechnical effluent production. For the fact that the tank is in open air, it has the inconvenience of generating odorous emissions;



**Fig. 1 – Block diagram of a traditional anaerobic digestion plant**

b) corn silage storage

The storage silo is made with galvanized sheet, of adequate size, with a capacity such as to have a material reserve of 56 m<sup>3</sup>, corresponding to 10 t/day;

c) corn silage shredding

The shredder is fed from the silo by gravity and its capacity depends from the hourly consumption of corn silage required by the mixer (417 kg/h);

d) effluent-corn silage mixing

The mixer is a screw conveyor type and is fed by effluent and corn silage; it is possible to change silage corn with grass (Liang et al., 2011). This operation is necessary to ensure homogeneity of the sewage and to prevent the formation of any sediment before its input into the anaerobic digester by gravity. The amount of corn silage is equal to 4.76% of the total. The quantity of treated mixture that feeds the digester is about 210 tonnes daily;

e) anaerobic digestion

The digester consists of a cylindrical reinforced concrete tank of the capacity of 2,915 m<sup>3</sup> and two agitators. At the base of the tank are positioned, on four levels, a series of pipes which, arranged in a circular ring, cover the circumference of the tank: within them circulate water at a temperature of 92°C to maintain a constant temperature of indigestate (mean temperature of water: 35°C).

After the loading phase, there is a continuous entrance flow of the effluent-corn silage mixture to compensate for the exit of the same amount of material (digestate at bottom and biogas at top). The real digestion step has a retention time of 35-40 days;

f) desulphurisation of biogas

This system has the purpose of breaking down the hydrogen sulphide (2-3%) and water vapour (20-25%) present in the biogas.

The system consists of a bio-scrubber (Gabriel et al., 2004) and the produced gas has a prevalence of biomethane with the presence of about 40% of CO<sub>2</sub>. The biogas produced is conveyed to the gasometer;

g) storage of biogas

The gasometer has the function of a constant pressure container and, although the dimensions are often considerable, is not suitable for contain large quantities of gas for a long-term storage, but it has the function of short-term regulation between gas production and gas consumption: in this way it is possible to serve peak demand, to compensate a stop production or a cyclic production.

The tank volume adapts to the amount of stored gas, while the pressure at which the gas is subjected in its interior depends from the weight of a movable roof: it is therefore used a gasometer with double membrane. The pressures are from 5 to 50 mbar, with a temperature between -30°C and +50°C which is also the maximum allowable gas temperature. The system is

equipped with a torch to burn the biogas in surplus in the case in which the engine cogeneration shuts;

h) electricity and heat generation using internal combustion engine

The cogeneration system consists of a Otto-cycle internal combustion engine powered by biomethane: it is coupled to a three-phase asynchronous alternator operating in parallel with the electricity transmission network and it can work in “island mode” as rescue group for the network, heat recovery system, electrical command and control panel and soundproof container.

The cogeneration system is also equipped with electricity meter, parallel interface panel to the ENEL network, GSM modem and motor circuit sink emergency.

The cogeneration system can operate with an external air temperature of 35°C and it has a water temperature for the district heating between 70°C (at the entrance of the heat exchanger) and 90°C (at the exit of the heat exchanger);

i) digestate homogenization

This phase, not expecting in plants built until 2006, must be introduced for new plants as the EU Directive 91/676/EEC requires the agronomic regulation use of zootechnical effluent.

For digestate homogenization phase it is used a cylindrical tank in which is placed the digestate together with sodium hydroxide in appropriate quantity (10% of the volume of entry). The Italian legislation (D.Lgs. 3 aprile 2006, n. 152 and subsequent modifications and additions) requires the storage of 90 days for solid fractions and 120-180 days for liquid fractions;

j) storage and purification of the homogenized

The biological purifier has the function of converting in active sludges the organic and inorganic substance contained in the digestate.

The digestate, initially, undergoes homogenization in a particular system that consists of a cylindrical reactor, with double mobile helix, made in stainless steel sheet of the volume of 8.1 m<sup>3</sup>, which allows to transform the incoming semi-solid

fluid with BOD equal to 25,000 mg/dm<sup>3</sup> in semifluid organic substance with BOD of 50-60,000 mg/dm<sup>3</sup>, by the addition of sodium hydroxide in a quantity equal to 10% of homogenizer volume. The reactor is fed continuously with digestate.

The homogenized accumulates on the bottom of the reactor, which is conveyed afterwards in the real biological purifier, which is a truncated conical reactor built in reinforced concrete having a total volume of 40 m<sup>3</sup>. The homogenized is accumulated inside and purified in a minimum time of 5 days.

The system operation requires that, at predetermined intervals, compressed air is introduced into the reactor to move all the material contained and stimulate, by aerobic bacteria, the production of active sludge, which is accumulated in the bottom of the purifier. The sludge is sent to the activated sludge storage. Moreover, the clarified water at the top of the purifier, is sucked and sent to the sewer or to surface waters;

k) storage and drying of the activated sludge before its spreading on agricultural lands

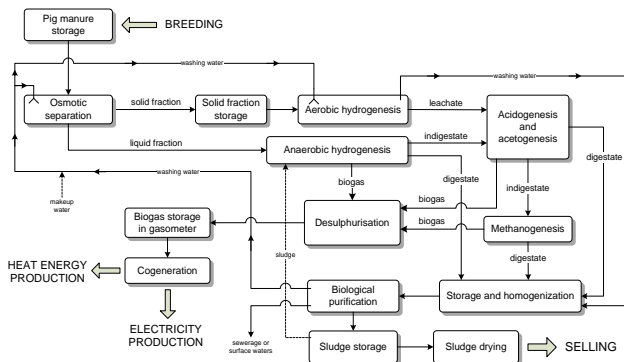
The activated sludge are stored and stabilized by pit drying or, forcedly, on a drying belt, for subsequent sale as fertilizer for agricultural purposes.

It's noted that, among the various problem that this plant system entails, assumes a relevant importance the quantity of ammonia which forms during the process: in fact, as ammonia acting as inhibitor of the reactions during the addition and mixing of new material (discontinuous system), leads to a reduction of process yield up to 50% (Chen et al., 2008), (Li et al., 2011), (Yenigum and Derimel, 2013).

## *2.2 Innovative anaerobic digestion process*

Considering again a system with a potential of 300 kW<sub>e</sub>, the innovative process may be divided into the following operational phases (see Fig. 2); it notes that this configuration do not use the corn silage or other primary additive as material

in input. All following data about volumes and capacity of reactors are obtained by theoretical calculations.



**Fig. 2 - Block diagram of an innovative anaerobic digestion process**

a) storage of zootechnical effluent from the pig farms

The storage is made up of a temporary storage tank, dimensioned for a maximum retention time of 7 days. The deposit is covered with waterproof tarpaulins so as to avoid effluents wash away and ensure the aeration to prevent abnormal fermentations, which can be averted with a suitable stirring system. The tank of parallelepiped shape having a volume of about 480 m<sup>3</sup>, is built in prefabricated and underground masonry panels;

b) osmotic separation between the solid fraction and the liquid one

It is used a truncated cone osmotic separator, having a semipermeable membrane and a scraper, which allows to separate the solid deposited on the membrane and transport it to the exit with a high BOD value. Has a treatment capacity of about 3.75 m<sup>3</sup>/h; furthermore the separator has a series of washing nozzles, placed in proximity of the vault, that use water coming from the biological purifier;

c) hydrogenesis aerobic

The system has 8 reactors in order to load one per day and allow the hydrogenesis aerobic process to work for the next 7



days. In this way for each day of the week is associated a specific reactor, while the eighth reactor is in reserve to allow cleaning and subsequent loading.

Each reactor is made up of a truncated conical shape tank, built in stainless steel sheet, suitably insulated, having a capacity of 2.5 m<sup>3</sup>, in which four lighting columns are installed to achieve, alternately, the luminous phase and dark one.

The designed capacity of the reactor is about 2.5 tonnes of solid per day, derived from zootechnical effluents. The reactor has, in the upper part, washing nozzles for cleaning by water, coming from osmotic phase and refrigeration system, which is then conveyed to biological purifier.

The reactor is heated by a coil traversed by water which allows to maintain the temperature of the material at 20-25°C, depending on the operating conditions of the reactor (20°C for the heterotrophic phase and 25°C for the autotrophic phase). At the exit you have the leachate, which is sent at the acidogenesis-acetogenesis reactor;

d) hydrogenesis anaerobic

It takes 4 truncated conical shape reactors, built in stainless steel sheet, suitably insulated, with a unit capacity of about 42 m<sup>3</sup> to allow the treatment of all lye coming from osmotic separator; the reactors operate continuously at temperature of 38-40°C, achieved by the heating resulting from the thermal recovery of the cogeneration engine, with a mean retention time of 5 days.

At full capacity, it is introduced lye and it is removed indigestate, which is conveyed to the acidogenesis-acetogenesis reactor, and biogas, which is conveyed to the desulfurizer;

e) acidogenesis and acetogenesis

It takes 2 truncated conical shape reactors, built in stainless steel sheet, suitably insulated, with a unit treatment capacity of about 145 m<sup>3</sup>, operating continuously at a temperature of 38-40°C and with a mean retention time of 12 days.

Each reactor is fed by the indigestate of anaerobic hydrogenesis and the leachate of aerobic hydrogenesis. At full capacity, the introduction of new indigestate and leachate and the extraction of indigestate, at different chemical-biological concentrations, from the acidogenesis-acetogenesis reactor is continuously, 24 hours per day, with a very limited flow.

Inside the reactor bacteria work by vertical gradient and they are supported by the recirculation system, whose flow depends by the rate of biological reaction. The produced indigestate is transported to the methanogenesis reactor, while the digestate is conveyed to the biological purifier;

f) methanogenesis

The proposed system is different from the traditional one, as the incoming substances, already decomposed in the previous phases, allow to accelerate the production of methane and, sometimes, hydrogen in thermophilic situation (48-50°C). The temperature range is very limited because of the fact that bacteria or micro-organisms in general, at such temperatures, have a maximum intensity of interaction or activity of degradation of the substances, with the production of the maximum amount of methane and hydrogen.

It is used 2 truncated conical shape reactors, built in stainless steel sheet, suitably insulated, with a unit treatment capacity of about 116 m<sup>3</sup> and a retention time of 8-12 days.

The reactor is continuously fed by indigestate coming from acidogenesis-acetogenesis processes; at output you have digestate, in the extent of 25% of the total volume of the reactor, which is conveyed to the biological purifier, and biogas, in the extent of 75%, which is conveyed to the desulfurizer;

g) desulphurisation

The system consists of two stainless steel pipes in which are inside inserted some meshes in inert plastic material, on top of which are positioned some iron filings, containing a mixture of pure iron, iron oxide and ferric chloride.

The two tubes come alternately into operation (operational phase and regeneration phase of the meshes with iron filings): the feed of the system is supplied from top to bottom, since the granule size of the iron oxide is greater than the mesh of the wire gauze and can not be therefore transported by the gaseous mixture which instead interacts with hydrogen sulfide and water vapor.

The produced gas mainly contains biomethane (approximately 60%) and CO<sub>2</sub> (40%) and is conveyed to the gasometer;

h) storage in gasometer

It has the same functionality of the system described for the traditional anaerobic digestion system;

i) electricity and heat generation with combustion engine

It has the same functionality of the system described for the traditional anaerobic digester system;

j) homogenization and biological purification

It has the same functionality of the system described for the traditional anaerobic digester system.

It is noted, however, that the tank is continuously fed by digestate, which flows from anaerobic hydrogenesis, acidogenesis-acetogenesis and methanogenesis processes, and, for a small part, from washing of the single reactor of aerobic hydrogenesis process;

k) storage and drying of the activated sludge before its spreading on agricultural land

It has the same functionality of the system described for the traditional anaerobic digester system.

To reduce environmental impact and costs, it is possible that sludges can return to anaerobic hydrogenesis process, in order to increase the production of biogas.

### **3. RESULTS AND DISCUSSION**

The comparison of the two molecular-biological plant systems is solved by dividing the bacterial strains, the micro-organism species and the selected, as well as those selectable, varieties in ecological niches, in order to have the maximum production and generational change. In the innovative system, each phase undergoes a volume increase, since the competition between the species present in the other phases decrease and the gradient of reaction is equally distributed.

In the two first stages of aerobic and anaerobic hydrogenesis process, the digestive action is mechanical, i.e. the task of microorganism is to break up organic matter into simpler materials, facilitating the role of acidogenesis ecosystem (Shah et al., 2014).

Among the acidogenesis and acetogenesis process there is a continuous gradient in which the microorganisms are consensual between them, since the wastes of some species are substrate for other. All the reactions of catabolic biosynthesis which occur in this stage have thermochemical prevalence and all are exergonically limited.

Passing from acidogenesis to acetogenesis stage, the acidification of the substrate induces the transformation in acetic acid and similar compounds, in which some of the biochemical reactions activates, influenced by reaction kinetics, with consequent development of an important volume of biogas.

In methanogenesis stage, there is, instead, a prevalence of reaction kinetics, but thermochemical aspect should not be neglected, since the system work in thermophilic conditions and 70% of biogas develops, according to the equations of mass and energy development resulting from the traditional anaerobic digestion process.

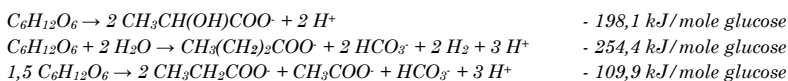
It notes that the reactions of anaerobic biodegradation are the same in the two systems, but the sequence is disadvantageous in the conventional system, since all stages

develop in a single reactor. In fact, when mixture, consisting of zootechnical effluent and crushed corn silage, is inserted into the traditional reactor, the following stages of acidogenesis, acetogenesis and methanogenesis are inhibited, since microorganisms of hydrogenesis anaerobic process (traditionally called hydrolysis) have a reactive priority. Such condition does not occur in the innovative system, as the phases are different in each reactor.

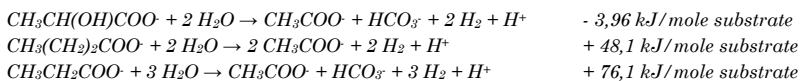
Also the biosynthesis reactions, that traditionally are discontinuous, have a operational continuity in the innovation system.

The sequence of biodegradation reactions, which have the production of bio-methane and hydrogen as their ultimate goal (Smolders et al., 1994), (Tracy and Flammino, 1987), (Fagundes et al., 2015), (Farai Muvhiiwa et al., 2015) is divided into three stages:

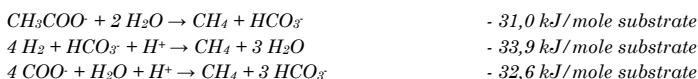
a) synthesis of important products (lactate, butyrate and propionate), which is expressed by the following main reactions:



b) degradation of important products, which is expressed by the following main reactions (Donoso-Bravo and Mairet, 2012):



c) methanogenesis, which is expressed by the following main reactions (Donoso-Bravo and Mairet, 2012):



Such reactions allow to determine an estimate of the quantity of required energy in the two anaerobic digestion configurations, since inside the two systems currently other reactions, difficult to determine, take place. The results achieved are summarized below.

It is evaluated the free energy required or supplied to the two systems (traditional and innovative), in the stages of fermentation, acidogenesis-acetogenesis and methanogenesis, multiplying the change of the standard Gibbs free energy with the number of moles of the substance per unit volume (Dolfing and Novak, 2015), (Yu et al., 2004).

The total Gibbs free energy supplied by the traditional system is equal to 2,829.6 kJ/m<sup>3</sup>, while the energy for the innovative system is equal to 3,213.0 kJ/m<sup>3</sup>. Therefore the efficiency improvement of the innovative system is about 13.5%, because the traditional system requires a greater energy supply from the outside to maintain the optimal thermodynamic conditions.

Furthermore, the two systems have different volumes in which the reactions develop; in the traditional system this volume is estimated at 32.4 m<sup>3</sup>, while in the innovative one is equal to 23.0 m<sup>3</sup>, taking into account the reaction coefficients as is deducible in literature (Kim and Gadd, 2008).

This difference is due to the fact that in the traditional system there is a discontinuous production of these reactions, previously quantified, since in addition to the main reactions of acidogenesis-acetogenesis, simultaneously the secondary reactions, characteristic of the hydrogenesis aerobic process, occur.

Instead, in the innovative process, there is no discontinuity, because the three reaction stages are separated and in the estimated volume take place with continuity only the main reactions.

It was therefore analyzed the energy and mass flow of the two system configurations (traditional and innovative),

taking into account the thermodynamic conditions that occur in reactors. Particularly:

a) traditional system

The thermal power consumption of the system, theoretically determined and compared with the experimental measurements carried out on the real plant, is equal to about 360 kW<sub>t</sub>, corresponding to the amount of heat required to maintain the internal temperature of the reactor in mesophilic conditions (35.5°C), in the situation of minimum outdoor temperature (-5°C), taking account of the amount of heat dispersed in pipes in which the heating fluid circulates and the amount of heat transferred to the zootechnical effluent and corn silage in order to increase their temperature (11°C).

The electricity consumption of the system, detected on the real plant unless the system of water purification, has been estimated about 50 kW<sub>e</sub>, corresponding to different components of the plant (electric motors of the moving system of the heating fluid, agitators, shredding systems of corn silage, Archimedes' pump used for last digestate extraction, mixing pump of the zootechnical effluent and silage corn, biogas fans from reactor to desulphuriser and from desulphuriser to gasometer, biogas compressor from gasometer to cogenerator, feed pumps of the homogenizer and sodium hydroxide, stirrer of homogenizer and pumps used to transport the homogenate to the biological purifier and sludge from the biological purifier to the dryer).

b) innovative system

The consumption of thermal energy of the system has been estimated about 160 kW<sub>t</sub>, corresponding to osmotic separation stage (temperature 14°C), aerobic and anaerobic hydrogenesis (respectively at the temperature of 25°C and 40°C), acidogenesis-acetogenesis (temperature 40°C) and methanogenesis (temperature 50°C) process and to biological treatment (temperature 20°C).

The consumption of electricity of the system has been estimated about 40 kW<sub>e</sub>, corresponding to the different plant

components (lighting columns, electric motors for effluent handling, scraper, feed pumps of lye and sludge, belt conveyor, feed pumps of the indigestate, leachate and washing water, fans and biogas compressor, feed pumps of the homogenizer and sodium hydroxide, stirrer of homogenizer and pumps used to transport the homogenate to the biological purifier and sludge from the biological purifier to the dryer).

#### **4. CONCLUSIONS**

The importance of comparing the installation system of the traditional anaerobic digestion with the innovative one is in evaluating the energy balance in each phase, relating it to the mechanics aspects of both systems.

As it is an innovative system, the estimate of the energies involved is the result of studies and experimental data made on traditional systems. After a careful analysis on the thermodynamic conditions of each stage, it is deduced that the biological process continuity promotes bio-methane production. Even if the innovative system is to be validated with an experimental installation, the theoretic studies conducted lead to the following conclusions: reduction of volume of the whole process and smaller electric and thermal energy consumption of the process at the same electric power generated.

#### **REFERENCES**

1. Alvarez R., Liden G., (2008), Semi-continuous co-digestion of solid slaughterhouse waste, zootechnical effluent, and fruit and vegetable waste, *Renewable Energy*, **33**, 726-734.
2. Biernacki P., Steinigeweg S., Borchert A., Uhlenhut F., (2013), Application of Anaerobic Digestion Model No. 1 for describing anaerobic digestion of grass, maize, green



- weed silage, and industrial glycerine, *Bioresource Technology*, **127**, 188-194.
3. Blumensaat F., Keller J., (2005), Modelling of two-stage anaerobic digestion using the IWA Anaerobic Digestion Model No. 1 (ADM1), *Water Research*, **39**, 171-183.
  4. Cecchi F., Bolzonella D., Pavan P., Macé S., Mata Alvarez J., (2011), Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste for Methane Production, *Research and Industrial Application, Reference Module in Earth System and Environmental Sciences, from Comprehensive Biotechnology*, **6**, 463-472.
  5. Chen Y., Cheng J.J., Creamer K.S., (2008), Inhibition of anaerobic digestion process: A review, *Bioresource Technology*, **99**, 4044-4064.
  6. Chen Z., Hu D., Zhang Z., Ren N., Zhu H., (2009), Modelling of two-phase anaerobic process treating traditional Chinese medicine wastewater with the IWA Anaerobic Digestion Model No. 1, *Bioresource Technology*, **100**, 4623-4631.
  7. Cheng J., Ji Y., Kong F., Chen X., (2013), Combined Mesophilic Anaerobic and Thermophilic Aerobic Digestion Process: Effect on Sludge Degradation and Variation of Sludge Property, *Applied Biochemistry and Biotechnology*, **171**, 1701-1714.
  8. Chen Y., Rößler B., Zielonka S., Lemmer A., Wonneberger A-M., Jungbluth T., (2014), The pressure effects on two-phase anaerobic digestion, *Applied Energy*, **116**, 409-415.
  9. Cuetos M.J., Gómez X., Otero M., Morán A., (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.
  10. Dareioti M.A., Dokianakis S.N., Stamatelatou K., Zafiri C., Kornaros M., (2009), Biogas production from

- anaerobic co-digestion of agroindustrial wastewaters under mesophilic conditions in a two-stage process, *Desalination*, **248**, 891-906.
11. Derbal K., Bencheikh-lehocine M., Cecchi F., Meniai A.H., Pavan P., (2009), Application of the IWA ADM1 model to simulate anaerobic co-digestion of organic waste with waste activated sludge in mesophilic condition, *Bioresource Technology*, **100**, 1539-1543.
  12. Dolfig J., Novak I. (2015): The Gibbs free energy of formation of halogenated benzenes, benzoates and phenols and their potential role as electron acceptors in anaerobic environments, *Biodegradation*, **26**, 15-17
  13. Donoso-Bravo A., Mailier J., Martin C., Rodriguez J., Aceves-Lara C.A., Wouwer A.V., (2011), Model selection, identification and validation in anaerobic digestion: A review, *Water Research*, **45**, 5347-5364.
  14. Donoso-Bravo A., Mairet F., (2012), Determining the limiting reaction in anaerobic digestion processes. How has this been tackled ?, *Journal of Chemical Technology and Biotechnology*, **87**, **10**, 1375-1378.
  15. Fagundes D.S., Previdelli Orrico Junior M.A., Amorim Orrico A.C., Seno L.O. (2015): Mathematical models of anaerobic digestion for the treatment of swine effluents, *Pesquisa Agropecuária Tropical (Agricultural Research in the Tropics)*, **45**, **2**, 172-179.
  16. Farai Muvhiiwa R., Hildebrandt D., Glasser D., Matambo T. (2015): A Thermodynamic Approach Toward Defining the Limits of Biogas Production, *AIChE Journal*, **61**, **12**, 4270-4276.
  17. Forster-Carneiro T., Pérez M., Romero L.I., (2008), Anaerobic digestion of municipal solid wastes: Dry thermophilic performance, *Bioresource Technology*, **99**, 8180-8184.
  18. Gabriel D., Cox H.H.J., Deshusses M.A., (2004), Conversion of Full-Scale Wet Scrubbers to Biotrickling

- Filters for H<sub>2</sub>S Control at Publicly Owned Treatment Works, *Journal of Environmental Engineering*, **130**, **10**, 1110-1117.
19. Golkowska K., Greger M., (2013), Anaerobic digestion of maize and cellulose under thermophilic and mesophilic conditions – A comparative study , *Biomass and Bioenergy*, **56**, 545-554.
  20. Hessami M.A., Christensen S., Gani R., (1996), Anaerobic digestion of household organic waste to produce biogas, *Renewable Energy*, **9**, 1-4, 954-957.
  21. Holm-Nielsen J.B., Al Seadi T., Oleskowicz-Popiel P., (2009), The future of anaerobic digestion and biogas utilization, *Bioresource Technology*, **100**, 5478-5484.
  22. Jang H.M., Park S.K., Ha G.H., Park J.M., (2013), Microbial community structure in a thermophilic aerobic digester used as a sludge pretreatment process for the mesophilic anaerobic digestion and the enhancement of methane production, *Bioresource Technology*, **145**, 80-89.
  23. Jang H.M., Cho H.U., Park S.K., Ha J.H., Park J.M., (2014), Influence of thermophilic aerobic digestion as a sludge pre-treatment and solids retention time of mesophilic anaerobic digestion on the methane production, sludge digestion and microbial communities in a sequential digestion process, *Water Research*, **48**, 1-14.
  24. Kim B.H., Gadd G.M., (2008), *Bacterial Physiology and Metabolism*, Cambridge University Press, New York.
  25. Korres N.E., O'Kiely P., Benzie J.A.H., West J.S., (2013), *Bioenergy Production by Anaerobic Digestion: Using Agricultural Biomass and Organic Wastes*, Milton Park, Abigdon, Oxon, Routledge.
  26. Lastella G., Testa C., Cornacchia G., Notornicola M., Voltasio F., Sharma V.K., (2002), Anaerobic digestion of semi-solid organic waste: biogas production and its

- purification, *Energy Conversion and Management*, **43**, 63-75.
27. Lauwers J., Appels L., Thompson I.P., Degrève J., Van Impe J.F., Dewil R., (2013), Mathematical modeling of anaerobic digestion of biomass and waste: Power and limitations, *Progress in Energy and Combustion Science*, **39**, 383-402.
28. Lee M-Y., Suh C-W., Ahn Y-T., Shin H-S., (2009), Variation of ADM1 by using temperature-phased anaerobic digestion (TPAD) operation, *Bioresource Technology*, **100**, 2816-2822.
29. Liang Y.-G., Zheng Z., Luo X-Z., Guo F.-H., Wang L-M., Zhang J-B., (2011), Effect of mesophilic and thermophilic conditions on changes of physicochemical characteristics of smooth cordgrass via dry digestion process, *Chemical Engineering Journal*, **168**, **2**, 544-552.
30. Liang Y., Zheng Z., Hua R., Luo X., (2011), A preliminary study of simultaneous lime treatment and dry digestion of smooth cord grass for biogas production, *Chemical Engineering Journal*, **174**, 175-181.
31. Li Y., Park S.Y., Zhu J., (2011), Solid-state anaerobic digestion for methane production from organic waste, *Renewable and Sustainable Energy Reviews*, **15**, 821-826.
32. Madsen M., Holm-Nielsen J.B., Esbensen K.H., (2011), Monitoring of anaerobic digestion processes: A review perspective, *Renewable and Sustainable Energy Reviews*, **15**, 3141- 3155.
33. Mata-Alvarez J., Macé S., Llabrés P., (2000), Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives, *Bioresource Technology*, **74**, 3-16.
34. Meabe E., Déléris S., Soroa S., Sancho L., (2013), Performance of anaerobic membrane bioreactor for

- sewage sludge treatment: Mesophilic and thermophilic processes, *Journal of Membrane Science*, **446**, 26-33.
35. Mehdizadeh S.N., Eskicioglu C., Milani A.S., Saha M., (2012), Empirical modeling of the effects of emerging pretreatment methods on anaerobic digestion of pulp mill biosolids, *Biochemical Engineering Journal*, **68**, 167–177.
36. Momoh O.L.Y., Anyata B.U., Saroj D.P., (2013), Development of simplified anaerobic digestion models (SADM's) for studying anaerobic biodegradability and kinetics of complex biomass, *Biochemical Engineering Journal*, **79**, 84–93.
37. Mudhoo A., (2012), *Biogas Production - Pretreatment Methods in Anaerobic Digestion*, J. Wiley & Sons, Hoboken, New Jersey.
38. Mudhoo A., Kumar S., (2013), Effects of heavy metals as stress factors on anaerobic digestion processes and biogas production from biomass, *International Journal of Environmental Science and Technology*, **10**, 1383-1398.
39. Muha I., Zielonka S., Lemmer A., Schönberg M., Linke B., Grillo A., Wittum G., (2013), Do two- phase biogas plants separate anaerobic digestion phases? A mathematical model for the distribution of anaerobic digestion phases among reactor stages, *Bioresource Technology*, **132**, 414–418.
40. Mumme J., Linke B., Tölle R., (2010), Novel upflow anaerobic solid-state (UASS) reactor, *Bioresource Technology*, **101**, 592–599.
41. Orozco A.M., Nizami A.S., Murphy J.D., Groom E., (2013), Optimizing the thermophilic hydrolysis of grass silage in a two-phase anaerobic digestion system, *Bioresource Technology*, **143**, 117-125.
42. Ozuolmez D., Na H., Lever M.A., Kjeldsen K.U., Jorgensen B.B., Plugge C. M. (2015): methanogenic

- archaea and sulfatereducing bacteria co-cultured on acetate: teamwork or coexistence?, *Microbiology*, 6, article 492, 1-12.
43. Ramirez I., Volcke E.I.P., Rajinikanth R., Steyer J-P., (2009), Modeling microbial diversity in anaerobic digestion through an extended ADM1 model, *Water Research*, **43**, 2787-2800.
44. Raposo F., De la Rubia R.A., Fernández-Cegri V., Borja R., (2011), Anaerobic digestion of solid organic substrates in batch mode: An overview relating to methane yields and experimental procedures, *Renewable and Sustainable Energy Reviews*, **16**, 861-877.
45. Shah F.A., Mamood Q., Shah M.M., Pervez A., Asad S.A., (2012), Microbial Ecology of Anaerobic Digesters: The Key Players of Anaerobiosis, *African Journal of Biotechnology*, **11**, 4127- 4139.
46. Shigematsu T., Tang Y., Kawaguchi H., Ninomiya K., Kijima J., Kobayashi T., Morimura S., Kida K., (2003), Effect of Dilution Rate on Structure of a Mesophilic Acetate-Degrading Methanogenic Community during Continuous Cultivation, *Journal of Bioscience and Bioengineering*, **96**, **6**, 547- 558.
47. Seghezze L., Zeeman G., van Liel J.G., Hamelers H.V.M., Lettinga G., (1998), A review: The anaerobic treatment of sewage in UASB and EGSB reactors, *Bioresources Technology*, **65**, **3**, 175-190.
48. Smolders G. J. F., Van Der Meji J., Van Loosdrecht M. C. M., Heijnen J. J., (1994), Stoichiometric model of the aerobic metabolism of the biological phosphorus removal process, *Biotechnology and Bioengineering*, **44**, 837-848.
49. Tang Y-Q., Matsui T., Morimura S., Wu X-L., Kida K., (2008), Effect of Temperature on Microbial Community of a Glucose-Degrading Methanogenic Consortium under Hyperthermophilic Chemostat Cultivation, *Journal of Bioscience and Bioengineering*, **106**, **2**, 180-187.

50. Tracy K. D., Flammino A., (1987), *Biochemistry and energetics of biological phosphorus removal*, Advances in Water Pollution Control 4: Biological Phosphate Removal from Wastewaters, ed. R. Ramadori, Pergamon Press, Oxford, 15-26.
51. Yenigun O., Derimel B., (2013), Ammonia inhibition in anaerobic digestion: A review, *Process Biochemistry*, **48**, 901-911.
52. Vavilin V.A., Fernandez B., Palatsi J., Flotats X., (2008), Hydrolysis kinetics in anaerobic degradation of particulate organic material: An overview, *Waste Management*, **28**, 939–951.
53. Zamanzadeh M., Parker W.J., Verastegui Y., Neufeld J.D., (2013), Biokinetics and bacterial communities of propionate oxidizing bacteria in phased anaerobic sludge digestion systems, *Water Research*, **47**, 1558-1569.
54. Zhao B-H., Mu Y., Dong F., Ni B-J., Zhao J-B., Sheng G-P., Yu, H-Q., Li Y-Y., Harada H., (2010), Dynamic Modeling the Anaerobic Reactor Startup Process, *Industria & Engineering Chemistry Research*, **49**, 7193-7200.
55. Yu H-Q., Mu Y., Fang H.P. (2004): Thermodynamic Analysis of Product Formation in Mesophilic Acidogenesis of Lactose – *Biotechnology and Bioengineering*, **87**, 7, 813-822.