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Theoretical Comparison between a Traditional Anaerobic Digestion and an Innovative One

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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.

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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), (Seghezzo 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), (Cuetos, 2008), (Dareioti, 2009), (Golkowska and Greger, 2013), (Holm-Nielsen, 2009), (Jang H.M. et al., 2013), (Lastella et al., 2002), (Lianga 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_e, 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^3, 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;

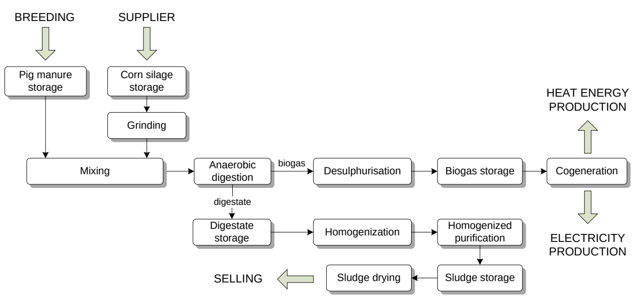

Fig. 1 – Block diagram of a traditional anaerobic digestion plant

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^3, 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^3 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_2. 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^3, which allows to transform the incoming semi-solid fluid with BOD equal to 25,000 mg/dm^3 in semifluid organic substance with BOD of 50-60,000 mg/dm^3, 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^3. 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$_e$, 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.

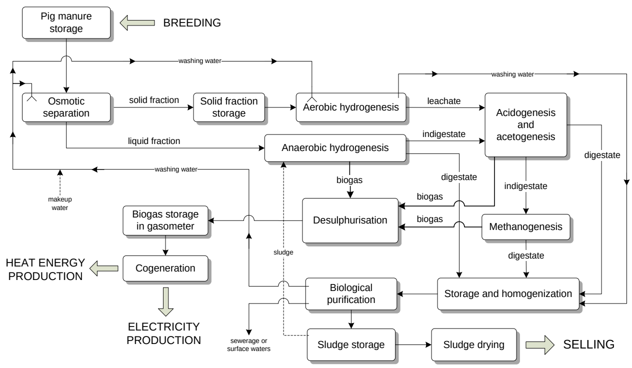

Fig. 2 - Block diagram of a innovative anaerobic digestion process

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^3, 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^3/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^3, 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^3 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^3, 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^3 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_2 (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 continuos 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:

$C_6H_{12}O_6 \rightarrow 2\ CH_3CH(OH)COO^- + 2\ H^+$	- 198,1 kJ/mole glucose
$C_6H_{12}O_6 + 2\ H_2O \rightarrow CH_3(CH_2)_2COO^- + 2\ HCO_3^- + 2\ H_2 + 3\ H^+$	- 254,4 kJ/mole glucose
$1{,}5\ C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2COO^- + CH_3COO^- + HCO_3^- + 3\ H^+$	- 109,9 kJ/mole glucose

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

$CH_3CH(OH)COO^- + 2\ H_2O \rightarrow CH_3COO^- + HCO_3^- + 2\ H_2 + H^+$	- 3,96 kJ/mole substrate
$CH_3(CH_2)_2COO^- + 2\ H_2O \rightarrow 2\ CH_3COO^- + 2\ H_2 + H^+$	+ 48,1 kJ/mole substrate
$CH_3CH_2COO^- + 3\ H_2O \rightarrow CH_3COO^- + HCO_3^- + 3\ H_2 + H^+$	+ 76,1 kJ/mole substrate

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

$CH_3COO^- + 2\ H_2O \rightarrow CH_4 + HCO_3^-$	- 31,0 kJ/mole substrate
$4\ H_2 + HCO_3^- + H^+ \rightarrow CH_4 + 3\ H_2O$	- 33,9 kJ/mole substrate
$4\ COO^- + H_2O + H^+ \rightarrow CH_4 + 3\ HCO_3^-$	- 32,6 kJ/mole substrate

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, multiplicating 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^3, while the energy for the innovative system is equal to 3,213.0 kJ/m^3. 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^3, while in the innovative one is equal to 23.0 m^3, 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_t, 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_e, 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_t, 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_e, 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 theoric 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.

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