Anaerobic digestion plants: yield calculation, analysis and how to improve the process and their products use

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Biogas, as renewable energy form, can properly substitute conventional sources of energy (fossil fuels, oil, etc.) which are causing ecological–environmental problems as fast increasing of CO_2 emissions.
This paper analyse different type of anaerobic processes, which difference depend of the alimentation to anaerobic digester. Several anaerobic plants were analysed with different reactors, different feedstock, agricultural by-products, slaughterhouse wastes conveniently used. For each plant has been analysed yield, biomass used, biogas composition, nitrogen balance and a final comparison of different technologies involved in the processes.

1. Introduction

Biogas is a biofuel produced by a fermentation of organic substrates by microbes under anaerobic condition and it is a mixture of gases; it consists mainly of methane (CH_4) and carbon dioxide (CO_2).
The gases formed are the waste products of the respiration of these decomposer microorganisms and the composition of the gases depends on the substance that is behind decomposed; methane makes up the combustible part of biogas.

Table 1: Composition of biogas

Gas	%
Methane (CH_4)	55-70
Carbon dioxide (CO_2)	30-45
Hydrogen sulphide (H_2S)	1-2
Hydrogen (H_2)	1-2
Ammonia (NH_3)	1-2
Carbon monoxide (CO)	Trace
Nitrogen (N_2)	Trace
Oxygen (O_2)	Trace

Compared with the aerobic decomposition of organic matter, the energy yield of anaerobic process is smaller. The growth rate of anaerobic bacteria is considerably lower that than aerobic bacteria and that the production of new biomass is less per gram decomposer organic matter.
The biomethanation process is divided into three steps: Hydrolysis, Fermentation-Acidogenesis and Methanogenesis, where different groups of bacteria are each responsible for a step.
This paper examines different types of anaerobic process, the difference of which depends on the feeding to the anaerobic digester, moreover the calculation of the yield for each different plant will be carried out and solutions will be sought to improve the performance of the process products. It is important to take in consideration that many factors can influence the methane production, the toxicity of the process, the toxicity of substrate and toxicity resulting from elements inhibiting.
The toxicity of the process it is connected to the optimization of the anaerobic digestion process, in fact the optimization has be conducted through the study of all the factors that contribute positively or negatively to influence the yield of the overall process. The presence of certain factors may inhibit or restrict growth bacterial population is that the yield of transformation of the substrate in the final product. The methanogenic bacteria are considered the most sensitive microorganisms of the entire bacterial population, whose task is to anaerobic conversion of organic matter to methane, as characterized by a low rate of growth.

The parameters that can adversely affect the whole process, are represented by the substrate itself and any elements inhibiting such heavy metals, salts, ammonia nitrogen (NH_4^+), pesticides and pharmaceuticals residual, detergents and disinfectants, solvents, inhibitors of chemical treatments for food preservation, etc. In some cases it is, however, noted that the anaerobic bacteria are able will tolerate some variety of toxic compounds and even biodegrade some. In addition, there may be also cases of acclimatization to the toxicity and reversibility of the same. The toxicity of substrate may be an inhibiting factor in that its concentration can be adjusted and/or slow down the reaction rate of the stages upcoming. Even some metabolic intermediates that form during the process of metabolism may limit the development of the upcoming stages, thereby, leading to an overall effect negative. For example, the propionate is a qualitatively important intermediate in the anaerobic digesters, usually second only to acetic acid. Although the concentration of propionate is usually quite low, its turnover is rather high (about one hour): the inhibition of the degradation of propionate, therefore, can lead to a sudden increase of its concentration, which can be toxic. The toxicity limit for the propionate appears to be around 3 g/l. The degradation of propionate is also influenced by the hydrogen which, in turn, can inhibit microbial degradation of ethanol and reversibly, the growth of many anaerobic bacteria. More generally, it has been reported in the literature as high concentrations of volatile fatty acids (VFA) can have toxic effects, mainly due to the resulting decrease of pH. Toxicity deriving from inhibitory elements is among the factors that can somehow inhibit the normal course of the methane process: there can be hydrogen sulphide, ammonia nitrogen, salinity, chloroform and other chlorinated disinfectants such as formaldehyde and phenols, as well as various metallic forms.

2. Anaerobic digestion efficiency

The anaerobic digestion applied in farms having cattle farms is influenced by the efficiency of conversion of biomass introduced in the chain of digestion.
It is taken as example an anaerobic digester fuelled by cow manure.
The data shown in Table 2 are average values derived from laboratory analysis done in several samples.
Knowing therefore the composition of the biomass and neglecting the amount of organic substance used for the synthesis cell, the estimate of the amount of methane (CH_4), carbon dioxide (CO_2), ammonia (NH_3) and hydrogen sulfide (H_2S) produced in anaerobic conditions can be carried out through the following relationship, first proposed by Buswell and Boruff and later extended by Sykes.

$$C_cH_hO_oN_nS_s + \frac{1}{4}(4c - h - 2o + 3n + 2s)H_2O \rightarrow \frac{1}{8}(4c - h + 2o + 3n + 2s)CO_2 + \frac{1}{8}(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S \quad (1)$$

The calculated conversion efficiency value is almost equivalent to that obtained empirically in several installations on farms powered by cow manure which is equal to 14.5%. This value obtained for anaerobic digester conversion can change if the biomasses that fuel the digester change and the boundary conditions change such as temperature, pH, bacteria compositions inside the digester. European Community plants have to respect Nitrates Directive (The Implementation of Council Directive 91/676/EEC concerning the Protection of Waters against Pollution caused by Nitrates from Agricultural Sources), therefore the reduction of nitrogen inside the digestate can be a way to reduce its nitrogen content and the volume of digestate what is spread on agricultural soil. Therefore, it’s extremely important to find methods to decrease the nitrogen content inside the digestate and in the same time to increase the biomass conversion efficiency of the digesters.

Table 2: Calculation of conversion efficiency based on percentage of elements by weight (Buswell's formula) for fresh cattle manure

% COMPOSITION			
a	C	%	39.09
b	H	%	4.61
c	O	%	26.68
d	N	%	0.83
e	S	%	0.25
	TOTAL	%	71.46
a'	atomic weight - C		12
b'	atomic weight - H		1
c'	atomic weight – O		16
d'	atomic weight – N		14
e'	atomic weight - S		32
EMPIRICAL FORMULA			
f	C – empirical formula		3.26
g	H – empirical formula		4.61
h	O – empirical formula		1.67
i	N – empirical formula		0.06
l	S – empirical formula		0.01
m	CO_2		1.49
n	CH_4		1.76
o	NH_3		0.06
p	H_2S		0.01
q	Total sum		3.32
% IN BIOGAS			
r	CO_2	%	44.9
s	CH_4	%	53.1
t	NH_3	%	1.8
u	H_2S	%	0.2
v	Total	%	100.0
% BIOGAS (WITHOUT N AND S)			
z	CO_2	%	45.8
z'	CH_4	%	54.2
APPROXIMATE ANALYSIS OF COW MANURE			
A	Moisture	%	13.9
B	Ash residual	%	13.7
C	Volatile matter	%	60.5
D	Fixed carbon	%	11.9
E	Cattle manure fresh	kg	1,000
F	Biodegradation conversion efficiency of carbon	%	90
G=(D/100*E)*F/100	C converted to biogas	kg	107.5
H=(G*z')/100	Weight of methane carbon (CH_4-C)	kg	58.2
I=H*(a'+4*b')/a'	Weight of methane (CH_4)	kg	77.6
I'=I/(z'/100)	Weight of biogas	kg	143.3
L	1 mol gas at Normal Condition (0 ˚C, 1 atm) = 22.4 l	l	22.4
M=I*1000/(a'+4*b')	Mols CH_4	mol	4,849.1
N=M*L	CH_4	l	108.62
O=N/1000	CH_4	Nm^3	108.6
P=O/(z'/100)	Biogas	Nm^3/t	200.6
Q=I'/E*100	Conversion efficiency of Anaerobic Digester	%	14.3

3. Yield, biomass used, biogas composition, nitrogen balance of various biogas plants in Italy

The main fuel of biogas plants considered in the farms are energy crops, cereals and livestock manure.
The choice of type of fuel is dictated by the organizational model of the farm, but also by the installed power capacity. During the fermentation process, livestock manure is less caloric than cereal; feeding a digester with a capacity of 1,000 kWe requires cereals or a mix of fuel.
Italy has put some time to development of renewable energy sources as a priority of its energy policy, together with the promotion of energy efficiency. The objectives of the strategy are: energy security, reduce energy costs for businesses and citizens, promotion of innovative technological chains, environmental protection (reduction of pollutant emissions and greenhouse-gas), and then, ultimately, sustainable development. Multifunctional farms and entrepreneurial farms represent the two main models followed by the farmers. It is very important to distinguish the two approaches to the energy production. According to the adopted models, the environmental consequence of the agro-energy production are very different. The primary objective for Italy is to lavish extraordinary commitment to increasing energy efficiency and reducing energy consumption. Such a strategy will contribute decisively to the achievement of the objectives concerning the reduction of greenhouse gas emissions and coverage of total energy consumption through renewable sources.
Incentive structures play an important role in determining the size of plants, as well as the choice of how the biogas produced will be used. Biogas is plugged into a system of regulations for renewable energies (together with solar, hydro and geothermal) in with priority is given electricity generation.
To explain the reasons that led to the spread of biogas plants, it is good to first identify the type of equipment to suit the style and the ultimate goals that the individual companies.
Organizational models consist of different practices whereby biogas system are integrated into existing farms.
The Italian biogas plants now can distribute natural gas through the network; rather they use the gas to produce electricity directly. In almost cases, the heat produced during gas burning is lost, with only a portion used within the farm. At best, the heat used consist of only 10% of total heat energy produced.
To understand the reasons why are built biogas plants, it is necessary to know the relationship between the mode of production of renewable energy and land use. The development of large biogas plants has changed the land use, before dedicated to the production of crops for human and animal nutrition and now intended for anaerobic digesters.
Were taken into account a number of plants distributed in the regions of northern Italy, in order to have a comparison between the various types of companies depending on the installed power and type of feeding.
Follows a description of the companies considering the location, the type of feeding and the installed power.
The yield of the plant calculated in Table 3 with the (2) is the conversion efficiency of anaerobic digester reported in Table 2.

$$Yield\ of\ the\ plant = \frac{Biogas\ Produced\ (t/y)}{Biomass\ Input\ (t/y)} \quad (2)$$

In Table 4 is reported the biogas analysis for each plant considered in this paper.
It also reports the value of biogas produced per ton of digested biomass in input and the tons of biogas per ton of digested biomass. As can be seen, the conversion yields of the various plants considered depend greatly on the biomass used but above all on the type of pre-treatment of the incoming biomass. In fact, in plants with large electrical power where a high energy concentration in biomass is required, it is preferred to use energy crops such as corn silage, while in small plants, animal sewage is used which has a low energy content but allows to create a source of income for suffering farms that need to mechanize their stables and renovate their agricultural machinery. Moreover, it is for this reason that it is necessary to encourage small energy production plants feeded by agricultural by-products distributed throughout the territory which, in addition to being a source of income, are also a good basis for supporting the electrical network with distributed micro-generation.
The other indicator that shows us the efficiency of the anaerobic digestion plant is the biogas produced per ton of digested biomass, also here it is possible to see that farms that mainly use residues from livestock farming have very low yields compared to those companies that use energy crops. The nitrogen present in the biomass entering the anaerobic digester is simply transported to the exit of the digester itself, which is why it is necessary to implement techniques to reduce the nitrate content present in the digestate. A new and used technique is that of thermal and chemical abatement, which consists in heating the digested biomass to temperatures around 70-90 ˚C in order to evaporate the ammonia from the digestate which can be easily sequestered and transformed into ammonium sulphate, when it is hit by a sulphuric acid shower in an abatement column. To do this it is sufficient to heat the biomass with the heat coming from the CHP (Combined Heat and Power Plant) which is usually never used completely on the farm.

Table 3: Yield, biomass used in input of the wet type process biogas plants in the North of Italy

Description	kgN/t*	Farm CO	Farm FM	Farm FO	Farm MA	Farm PR	Farm SC
Electrical Power (kW)		999	999	999	999	99	999
Cattle manure (t/d)	2.8	18.4			40	2	6
Cattle slurry (t/d)	0.18	13				6.5	
Corn gluten feed (t/d)	4.8						4
Corn silage (t/d)	4.8		21.9	32	33	1	10.5
Crude glycerine (t/d)	nd			0.5			
Pasta soapy (t/d)	13.86			5			
Pig slurry (t/d)	4.92			1.5			
Poultry manure (t/d)	31.49					1	
Ryegrass silage (t/d)	4.2		10.9				
SW (t/d)	3.99	12.6					
Serum (t/d)	0.288	3					
Sorghum (t/d)	3.2	24.7	16.4	0.3			9
Triticale (t/d)	4.27						17
Wheat flour (t/d)	10			12.5			0.7
Biomass input (t/y)		28,404	21,000	18,907	26,645	3,833	18,856
Biomass output (t/y)		25,847	18,141	15,882	23,448	3,564	14,065
Biogas produced (Nm^3/y)		3,670,440	4,026,502	4,255,487	4,380,000	389,025	4,255,715
Biogas produced (t/y)		2,606	2,859	3,021	3,110	276	3,022
Biogas ($Nm^3/t_{digested\_biomass}$)		1,435	1,408	1,407	1,370	1,446	888
Biogas ($t_{biogas}/t_{digested\_biomass}$)		1.02	1.00	0.99	0.97	1.03	0.63
Nitrogen content (tN/y)		67	74	130	99	16	71
Yield of the plant (%)		9.2	14	16	12	7.2	16

CO – Colombara (Padua), FM – Finato Martinati (Verona), FO – Foina (Pavia), MA – Mantovanelli (Verona), PR – Pizzolo (Vicenza), SC – Santa Caterina (Pavia), source data 2019, (*) as it is, SW – Pasteurized Slaughterhouse Waste, nd - not detected

Table 4: Biogas composition of wet type process biogas plants in the North of Italy

Description	Temperature (˚C)	CH_4 (%)	O_2 (%)	H_2S (ppm)
Farm CO	42	54	0.6	90
Farm FM	44	50	0.3	110
Farm FO	42	55	0.7	70
Farm MA	42	51	0.8	120
Farm PR	42	60	0.2	140
Farm SC	46	53	0.7	68

CO – Colombara (Padua), FM – Finato Martinati (Verona), FO – Foina (Pavia), MA – Mantovanelli (Verona), PR – Pizzolo (Vicenza), SC – Santa Caterina (Pavia), source data 2019

3.1 Comparison of different technologies involved in the process of anaerobic digestion to improve the efficiency of the transformation of biomass in biogas

To increase the efficiency of the transformation of the biomass to be digested into biogas, there are various techniques, which can be grouped into physical, biological, thermal and chemical treatments.
Physical treatments, such as shredding and milling, are most likely the cheapest ones, together with chemical treatments, in the case of using cheap chemicals such as, for example, lime (C_aOH). Even the heat treatment can be included among the relatively cheap ones, as it is possible to use the excess heat produced by the CHP (Combined Heat and Power Plant), in the case of treatments at temperatures around 100 °C, while for those at higher temperatures the treatment certainly becomes more expensive and difficult to carry out on the farm. Therefore in economic terms, both physical and biological treatments are the least expensive, while heat treatments at high temperatures and chemical treatments with strong acids or bases imply the creation of more complex and expensive structures, furthermore the latter must be equipped with appropriate safety devices for the operator. In terms of time, the most expensive treatments are the biological ones, for which, often, the

bacteria used need long periods of activation, and the chemical ones, when substances are used which, altering some chemical parameters of the biomass (for example the pH), require their correction first insertion of biomass into the digester, to avoid inhibiting the anaerobic digestion process. Heat treatments require the use of a reactor capable of reaching high temperatures in a short time, withstanding high pressures and allowing a rapid decline of both these operating parameters at the end of the treatment. The temperature range in which it is operated is between 60 °C and 120 °C, with treatment times around 30 minutes.
The lignocellulosic biomasses that are treated at a temperature of 120 °C for a time equal to 30 minutes, are divided into:

- crop residues (corn stalks, wheat straw, rice straw, barley straw and rice husk);
- biomass of zootechnical origin (solid fraction of fresh pig slurry, solid fraction of pig slurry codigested in the plant with hydraulic retention time (HRT) of 40 days and solid fraction of codigested bovine slurry in the plant with hydraulic retention time of 100 days). The heat treatment at 120 °C is difficult to carry out on the farm as it requires equipment with high levels of safety for the protection of the operator.

The best results to increase the transformation efficiency of biomass into biogas are obtained on a scale from highest to lowest with physical, thermal, chemical and biological treatment.

4. Conclusions

This paper covered the calculation of the yield of the biogas plants, so as to define a percentage conversion into biogas in function of the biomass fed. Analysis of different companies have derived the conversion efficiencies for different types of power. As showed in Table 3 biomass with the highest potential for biogas production appear to be energy crops such as corn and wheat. As expected, in fact, companies that have present a high yield (16%) appear to be those who like power primarily use these biomasses. As found in the plants, the fed is never given by a single biomass, but using different combinations of them. It is the combination of the different biomass which yields the performance of individual plants. It is show that the use of energy crops give the high yield and the combination with manure or sewage decrease it. The use of only manure and sewage give a low yield in confront to the other type of feeding. At the same time, it has also to consider that there are the ethic aspect to use of energy crops to produce electricity that concern the environmental impact of the biogas plants. The use of energy crops provides yields of conversion very high, instead the use of by-products such vegetable waste residuals or animal waste, it causes that the conversion yield are much lower. This is a different type of management and it is different from previous one, and it is often applies to small and medium size of the plants. The conclusions that can be drawn regarding why the different types of plant are management, which starts at the planning of them. Biogas plants can be considered energy production plants from renewable sources and do not cause significant damage to the environment or human health. They must however, be designed and managed to the corporate level, so that they can use the waste produced. The future for system of this type in therefore restricted to small and medium size companies, which can truly be considered renewable and clean energy.

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