Above ground part of common reed to enhance anaerobic co-digestion of farm biomasses: Potential, monitoring and efficiency

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Abstract

This paper shows that common reeds used in phytoremediation plants can successfully disposed of in anaerobic digestion reactors. At mesophilic condition the following were investigated: biogas yield resulting from an anaerobic co-digestion campaign of mixtures of cattle slurry, cheese whey and aboveground biomass of *Phragmites australis*, rates of production of methane, removal efficiencies of chemical oxygen demand (COD) and bio-methane yield (BMY). The resulting concentration of methane in the biogas was between 53-56%. Maximum removal efficiencies for COD was 70%. The mixture of 50% cattle

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slurry, 40% cheese whey and 10% of aboveground parts of *Phragmites australis* achieved an Organic Loading Rate (OLR) of 3.3 g-VS/l-d with a methane yield of 241 l-CH_4/kg-VS. A high digestate methane potential with a high OLR in the feed was also tested, with a result of 219 l-CH_4/kg-VS.

Keywords Anaerobic co-digestion - Digestate methane yield - Whey - *Phragmites australis* – COD reduction

1. Introduction

EEC Directive 91/271, concerning urban and industrial wastewater, rules that the wastewater produced from farming and industrial production must now be subjected to treatment. A low cost solution are phytoremediation systems that are becoming widely used for the treatment of wastewater. The vegetal species used in most of these systems are part of the common reed family. The common reed is currently the most frequently used plant inside phytoremediation systems. They are also one of the most widespread vascular plants on Earth and are one of the dominant plants in Europe. *Phragmites australis* is a macrophyte often used to phytoremediate wastewater coming from urban sewage, but more frequently, from farming and its aboveground parts are generally cut twice a year.

To date, research has focused mainly on the strategies used in the big scale management of these plants (Hanssons et al, 2004, Kuhlman et al., 2013 and Risén et al., 2013). Showed that the aboveground parts of the common reed can be used to produce bio-methane. However, very little research has been carried out with regard to anaerobic co-digestion (A.D.). A productive final destination for the aboveground parts of common reed have been studied by Risén et al. (2013). This allows mixing different kinds of biomasses that need to be treated before disposal. The co-digestion of different kinds of biomass brings the Carbon:Nitrogen ratio into the optimal range, indicated in 20/1 – 30/1 by Parkin and Owen (1986), 10/1 – 30/1 by Schattauer and Weiland (2004), but also enhances the biomethane yield.

This paper reports on a study of enhancement of common reed co-digestion. C:N ratio high value influences CH4 production as the carbon cannot optimally be converted to CH4. The low values obtained for C:N ratio implies that the feedstock could result in a high total ammonia nitrogen (TAN) release and a high volatile fatty acids (VFAs) accumulation inside the digester (e.g. cattle slurry and whey co-digestion). As demonstrated by Parkin and Owen (1986) both TAN and VFAs are fundamental intermediates and potential inhibitors in the anaerobic digestion process. A working method to avoid excessive ammonia accumulation is to adjust low feedstock C:N ratios by adding high carbon content materials such as the aboveground biomass of *Phragmites australis*. Several examples of anaerobic co-digestion of different substrates can be found in scientific literature. Sosnowaki et al. (2003) studied the co-digestion of sewage sludge and municipal solid waste (MSW). Callaghan et al. (2002) investigated co-digestion of cattle manure/slurry with different kinds of fruit, vegetable wastes and chicken manures. In both cases successful blending of high C:N and low C:N feedstock improve digester performance and bring the following benefits of co-digestion: dilution of potentially toxic ammonia, allowing for an increased loading rate and an improved biogas yield.

The present study investigated the feasibility of anaerobic co-digestion of a previously tested mixture (cow manure and whey) with the addition of aboveground parts of *Phragmites australis* let out from a phytoremediation plant that treats cheese factory wastewater. The purpose was to investigate how an important variation in the feeding mixture can affect the methane production during co-digestion. The quality criteria for anaerobic digestion of selected substrates were established, and the suitability of *Phragmites australis* in the co-digestion and achievable methane yields was determined. Furthermore, the digestate methane yield potential was evaluated, as well as the Chemical Oxygen Demand (COD) removal efficiencies, and energy assessments were performed.

A full scale AD process produces unstable digestate and considerable biogas can be obtained. An investigation was therefore performed to compare this residual biogas potential (BMP) with the measurement of the initial biogas potential (BMP of the feeding materials).

This investigation helped to evaluate the full-scale AD process. An experimental campaign was conducted using a Continuous Stirred Tank Reactor of 128 L under standard temperature and pressure conditions (STP). Two benefits were obtained: first, the *Phragmites australis* used for the replacement of the cheese whey was derived from a phytoremediation plant treating its biomass. Second, an addition of carbon inside the substrate brought a more optimal C:N ratio.

2. Materials and methods

A pilot scale anaerobic digester was used for conducting the test. It had the following principal components: anaerobic reactor, gasometer and feed chamber. The size of the reactor was not relevant in the evaluation of the methane yield as this parameter was calculated under Standard Temperature and Pressure (STP) and expressed as CH_4 liter/kilograms of volatile solids. The only related variable was the quantity of volatile solids inserted inside the reactor.

2.1 Pilot device

The reactor covered a surface of 1.20 m^2, was 2.30 m height (Fig. 1). The reactor had a 316 stainless steel tank realized by a cylinder 90 cm high with a diameter of 40.3 cm, closed by two caps on the top and on the bottom, for a total volume of 128 l and a working volume of about 100 l. It was equipped by a mixer system with a blade propeller and a scraper on the bottom, both 316 stainless steel made and activated by a variable speed electric engine controlled by an inverter. The digester and the gasometer were equipped with a complete probe monitoring system including: a temperature probe inserted on one side of the reactor; a temperature and a pressure probes on the gas holder; a pH probe inserted inside the digester. The temperature was automatically controlled to remain inside mesophilic range and it was regulated by an electrical resistance (15 m). It was wrapped around the reactor and covered with insulating film to maintain the temperature near 35°C. The system was equipped with a small tank to collect condense, designed to be emptied automatically. The indirect measure of biogas yield was obtained with the movement of a slide-wired potentiometer, which was linked from one side with the gasometer upper parts and fixed with the chassis from the other. The operational pressure was about 9-10 mBar. The outlet pipe was equipped with a solenoid valve activated by a relay to allow the automatic discharge of the produced biogas. This system was described in details and used in a previous experience (Comino et al., 2012).

2.2 Phytoremediation plant

The constructed wetland for the diary “Laiterie Cooperative Valdigne” in Morgex (Valle d’Aosta, Italy) was built both to respect the environmental resources and to give a contribute to the development of such technology. It consists on a fat-removal unit and a basin for the storage and the distribution of the wastewater which precede three pythoremediation beds (Fig. 2): the first two are parallel and they work as submerged vertical flow wetland with gravel medium for a total area of 180 m^2, the last is a submerged horizontal flow wetland with sand medium and a total area of 360 m^2. These beds are planted with *Phragmites Australis* (CAV.) *Trin. Ex Steud.*, with a density of about 4 plants/m^2. At the time of the biomass harvest, the system is two years old. Deep description, system efficiencies and inlet/outlet wastewater analysis of the constructed wetland were already presented in a dedicated work (Comino et al., 2011).

2.3 Feed material

The feed biomass used for the realization of the two campaigns was composed of cow manure, cheese whey and the aboveground parts of *Phragmites australis*. The cow manure and the fresh cheese whey were both collected at the livestock farm “Fontanacervo” located in Villastellone (Turin – Italy). The collected biomass that was not immediately used to fill the reactors for the startup phase, was stored inside a refrigerator at about 4°C. The aboveground parts of *Phragmites australis* (almost 7 kg of fresh biomass) was collected from the phytoremediation plant described above and stored inside a 50 L barrel. The *Phragmites* biomass was first spread on a large surface and dried on a thin layer for 24 h at about 60°C. Then it was chopped into a smaller size of about 2 mm (Mshandete et al. 2006). The volatile solids were equal to 9.1 % in the cow manure, 4.5% in the cheese whey and 81% in the dried *Phragmites*; BOD_5 values were obtained for cow manure and cheese whey and were equal to 39,000 mg/l, 59,000 mg/l, the COD were equal to 120,000 mg/l, 74,400 mg/l respectively. The influent and effluent details are presented in Table 1 and Table 2.

2.4 Startup tests

The reactor was initially filled with only cattle slurry to obtain a stable anaerobic digestion under batch feeding conditions. About 80 kg were used for the scaled-up device. During the startup phase it is important to fill in with only cattle slurry the reactor to avoid the risk of a process collapse due to the whey trend to acidify very rapidly (Comino et al. 2012). Startup tests lasted 42 days. The substrate was stirred every 2 days for 30 min and the produced biogas was analyzed to monitor the quality.

2.5 Co-digestion test

After the startup phase co-digestion of test mixture was started. The feeding ratio was implemented as follow: the total processed quantity was equal to 55 kg of mixture (50%

cattle slurry, 40% cheese whey and 10% *Phragmites australis*). The slight differences between the startup quantity (80 Kg) and the co-digestion one (55 Kg) was due to facilitate the loading/unloading operations. So the first step was to reduce the total volume inside the anaerobic reactor from 80 to 55 Kg. Then the co-digestion feeding strategy was adopted and about 5 kg of substrate was removed and a 5 kg mixture (2.5 kg of manure, 2 kg of cheese whey and 0.5 kg of Phragmites australis) was loaded inside the reactor. Each test lasted 34 days of fed-batch feeding, plus a week of anaerobic rest with no feeding (batch condition). Feeding of the reactor was done 3 times a week until the complete replacement of the initial biomass. Such as was observed in past experience no purging with nitrogen was necessary. It was observed that less than 1% oxygen in the reactor volume did not adversely affect the test. The probes inside the system were calibrated before the beginning of the test. The gas production was checked at least twice a day via remote control. For the campaign the demonstrated different mixing intensity effect (Kaparaju et al. 2008), and the consequence of particle size on biogas yield (Mshandete et al. 2006) were taken in consideration. The substrate was stirred every time a feeding operation was performed for about 30-45 min. The temperature inside the reactor was always maintained at 35.5 °C ± 0.5. Between one feed and the other no stirring was performed inside the reactor. The gasometer was equipped with electronic controlled electro valves that allowed biogas discharge when reached preestablished values. pH, temperatures, pressure and gasometer vertical movements were all monitored at 5-min intervals. After the last feed, the system was left undisturbed for almost 7 days to evaluate biogas production stabilization. Substrate samples for the chemical analysis were collected at the end of the test (Tab. 2).

2.6 Digestate methane yield tests (DMY)

After the co-digestion was started a monitoring test without discharge of any biomass from the previous one. Indeed it was expected that the digestate still contain a considerable amount of undigested organic matter with a high OLR and a relatively short HRT. The substrates were stirred every two days for 45-min when biogas samples were collected. Main systems parameters were constantly checked including methane concentration inside the biogas. The anaerobic reactor remained sealed during the experimentation period. After 32 days of retention, the test was concluded and samples collected for chemical analysis (Tab. 2).

2.7 Bio-methane yield

To allow direct comparison with full-scale plants the bio-methane yield (BMY_1) of the co-digestion test was determinate, by using the following equation presented by Schievano et al. (2011):

$$BMY_1(\%) = \frac{BMP_{in} * TS_{in} - BMP_{out} * TS_{out}}{BMP_{in} * TS_{in}} * 100; \qquad (1)$$

Where BMP_{in} is the bio-methane potential in the fed mixture, BMP_{out} is the bio-methane potential in the output digestate, TS_{in} are the total solids fed during the observed period and TS_{out} are the total solids output with digestate during observed period. The BMY_1 obtained with Eq. (1), can be compared to the effective specific methane produced (SMP) in a full-scale plants and calculated with the following equation:

$$BMY_2(\%) = {}^{SMP}/_{BMP_{in}} * 100; \qquad (2)$$

2.7 Chemical analysis and procedures

The feed materials and obtained digestate were stored at 4 °C immediately after sampling. Chemical analyses were performed within 48 h in an accredited laboratory. BOD_5 was analyzed with the IRSA-CNR n°. 5100 A/94 method; COD with the IRSA-CNR n°. 5110/94 method; pH samples with IRSA-CNR Quad 100 method 2080/94 and inside the reactors with pH probes. Density was evaluated with the EMRO/012/1999 method; 105 °C residual, and the 550°C residual as the Total Volatile Solids were obtained with the IRSA-CNR Quad. 64 n°. 2.4.2/84 method. Ammonia was evaluated following the IRSA/APAT guidelines 29/2003 method n°. 4030C. Volatile Fatty Acids (C1-C6) were measured with the EMGC 003/1999 method. The *Phragmites australis* calorific value was calculated according to the ASTM D 240 method. A GA-2000 gas analyzer was used for the real time biogas monitoring. The monitored parameters were CH_4, CO_2, O_2, CO and H_2S, as well barometric pressure and relative pressure inside the gasometer. Organic loading rate (OLR) and hydraulic retention time (HRT) were calculated based on the regular additions. The data collected by the data logger were analyzed at the end of each test and processed using an own made database to evaluate different analytic parameters.

3 Results and discussion

3.1 Startup test

During the first 42 days, limited biogas production can be observed (Fig. 3). The pH value, which is not shown, increased in the first 2 days from about 6.9 to 7.8. This behavior anticipated an increase in biogas production which then reached a maximum between days 4 and 6 and then stabilized (Fig. 4a). A total of about 979 l of biogas was produced (Fig. 3). Considering that CH_4 inside the biogas was 55.4% the total amount of produced methane was 543 l. Following the methodology to obtain the specific bio-methane productions on VS basis with a total of 3.088 kg of VS inserted in the reactor was obtained a 174.8 l-CH4/kg-VS for 42 days of active anaerobic digestion. The startup followed the expected behavior and trend of biogas production from cattle manure. Similar values were found by Amon et al. (2007), Brachtl (2000), Thomè-Kozmiensky (1995) and Comino (2010, 2012). The ranges for the production of biogas, cited above, are all similar to what was obtained during the startup, which was 317.03 l-biogas/kg-VS.

3.1 Co-digestion tests

The use of a biomass mixture with 50% cheese whey and 50% cattle manure was proved suitable and effective to produce methane (Comino et al. 2012). The addition of aboveground biomass of *Phragmites australis*, to this mixture, allows to evaluate if a reduction of whey could change biogas production in quality and quantity. The different composition inside the substrates shows the methane yield at increasing OLR.

After a start-up phase with an OLR established inside the optimal range at about 0.9 g-VS/l-d, the test investigated the scaled-up reactor behavior using an OLR values equal to 3.28 g-VS/l-d (Tab. 3). The pH monitoring showed very smooth fluctuation during the test, the periodic unloading/loading operations were not clearly visible. The biogas production is presented in Figure 3 and the daily biogas production in Figure 4b. The final rest period of about a week showed a very smooth and progressive reduction of biogas production rate. No accumulation of undegraded material was observed inside the digester. The methane proportion inside the produced biogas with the scaled-up reactor (50% cattle slurry, 40% whey and 10% *Phragmites*) had an average value of 54.1%, a maximum value of 58.9% and a minimum of 46.5% (Fig. 3). It started to stabilize at the end of the test, while during the most part of the experiment followed a performance related to the feed operation. The obtained methane yield was equal to 241 l-CH_4/kg-VS with an OLR of 3.28 g-VS/l-d. In terms of COD were found the following values equal to 110 g/l, OLR= 137.5 g, COD/l_R and HRT=44 days. As visible in Fig. 3 the reactor continued to produce biogas smoothly, the total produced volume was equal to 3534.8 l with a COD reduction of 53% (Tab. 5).

3.3 Digestate Methane Yield (DMY) tests

To confirm the data obtained during the campaign was taken in consideration the realization of a theoretical methane yield, but it will bring a series of uncertainties that will be very difficult to discuss. The model originally developed by Buswell and Boruff (1932), that is able to estimates theoretical methane concentration starting from the chemical composition of organic substrate (C, H, N and S), do not integrate the influence of lignin and assume a total transformation of the element in CH_4 (that is not true under real conditions). Also, carbon content of a feed material can be used in combination with Buswell’s equation to estimate methane production, but it is necessary to assume what proportion of the feed material is degraded in the process and in this case, with a mix of three different materials, it will be very difficult to evaluate a real value. Another issue was the fact that a good model needs a detailed database as input factors, and this was not the case as the used materials and mix ratios were used for the first time. For all these reasons it was preferred to realize a Digestate Methane Yield (DMY) test after the experiment, in this way was possible to estimate the residual biogas/methane potential. A tests with a batch-fed regime was performed, as described in paragraph 2.5, after the co-digestion one.

The test was carried out after the co-digestion with 50:40:10 mixture, an estimated OLR of about 1.1 g-VS/l-d, that produced a total quantity of biogas equal to 782.7 l. Considering a CH_4 proportion of 53.6%, this amount corresponded to 419,8 l of methane (Fig. 3). The digestate methane yield was 218.9 l-CH_4/kg-VS with a VS estimated value of 1.9 kg, obtained from the chemical analysis taken at the end of the co-digestion test. This value indicates that the digestate potential is very high, but, as visible in Figure 4c, the daily production is steady. In a real scale process digestate can yield an important amount of biogas that could be used to produce electricity (i.e. 0.9 kWh per t/d with the above values). Data in literature shown that the methane yields obtained by several studies are sensible lower than the one presented in this paper (Hansen et al. 2006; Lethomaki et al. 2008; Menardo et al. 2011).

3.4 Discussion

No direct comparison can be made with other studies, as this substrate was never tested before, but few experiences were conducted in the past about the digestion of common reed alone or in co-digestion with other organic substrate. Renborg (1984) and Brolin et al. (1988) reported a methane production of 180 l-CH_4/kg-VS conducting a small-scale studies using summer harvested reed. Risén et al. (2013) realized a test using two 30L CSTR digesters with an operating temperature of 52°C and 24 days of HRT. The substrate was a mixture of common reed and five different fractions of organic material (Slaughterhouse waste – 38%; Cattle manure slurry – 30%; Milk plasma permeate – 15%; Sludge – 12%; Potato residues – 5%) obtaining a methane production from reed addition of about 219 l-CH_4/kg-VS. In a test conducted by the authors with pre-treated crop silage and cattle slurry the obtained value was equal to 249 l-CH_4/kg-VS with an OLR of 5.15 g-VS/l-d (Comino et al. 2010). Another experiment conducted with 50% of cattle slurry and 50% of whey had shown a methane yield of 343.4 l-CH_4/kg-VS with an OLR of 2.65 g-VS/l-d (Comino et al. 2012). Few experiments were carried out on co-digestion of cattle slurry and cheese whey. In the past, for these kind of substrates, anaerobic digestion was principally used as a wastewater treatment method, and not considered as a system to produce energy. Lehtomaki et al. (2007) in a study with several energy crops and cow manure mixture, found methane yields between 149 and 268 l-CH_4/kg-VS. In the high OLR test conducted by Lindorfer et al. (2008) was found methane yields between 360 and 400 l-CH_4/kg-VS. A mix of whey and cow manure with a 2:1 ratio was tested successfully by Lo and Liao (1989), they obtained a methane yield equal to 222 l-CH4/kg-VS. The presented results show that anaerobic digestion of cattle slurry, cheese whey with *Phragmites australis* could be successfully achieved without the use of chemicals (for pH correction) with a 50:40:10 substrate. As the aboveground part of the *Phragmites* was dry (Table 1) a liquid fraction was required to maintain sufficiently wet the substrate. Normally to compensate this situation the substrate was diluted with water. However, this experiment demonstrated that whey can be used as an ideal substitute for water, as even if contribute to increase the overall COD, the COD reduction in both test campaign were greater than 50%. Whey also contribute to add needed nutrients and vitamins to the microbiota.

Other studies with different types of biomass mixture, Stewart (1980) and Jarvis et al. (1997), have observed a maximum OLR of 6.7 kg-TS/m^3-d. Nordberg et al. (2007) have reached a maximum OLR equal to 3 g-VS/l-d in a trial with alfalfa silage that brought to a process breakdown. In past tests a working and productive process with an OLR value equal to 5.15 g-VS/l-d was obtained, but when reached a OLR of 7.78 g-VS/l-d the system rapidly breakdown (Comino et al. 2010). With a high OLR of 6.35 g-VS/l-d the mostly affected parameter is the residual methane potential that, as described in the next paragraph, could still remain high.

The BMY_1 indicated relatively high efficiency of the lab-scale digester (78%) (Table 3). Observing the daily biogas production (Fig.4b) can be noticed a couple of slight inhibition of the methanogenic activity, occurred between days 10 to 14 and 21 to 24, mainly due to a probably increased lignin content. Johnsson (1986) reported that is important that the reed is not harvested too late in the growing season, since the lignin content will be higher.

With the presented result, considering the test conducted with the scaled-up reactor it would be possible to obtain electricity production of about 2.9 kWh per 1 t/d with a CHP technology with a considered efficiency of 36%. This kind of mixture has an energy potential with the same order of magnitude of the energy crop and livestock waste co-digestion. The obtained value is lower if compared to what is possible to obtain with energy crops co-digestion, but the environmental benefits are much higher. Also the use of phytoremediation plants for anaerobic co-digestion is a new possibility that is still not investigated adequately. Different types of species, specifically used for this scope, more optimized mixture of biomass inside the reactor can bring higher electricity production.

4 Conclusion

The results of this study show that the co-digestion, without induced pH correction, of typical cheese factory biomasses and a small fraction of *Phragmites australis* coming from a phytoremediation plant, is efficient and effective. A mixture of 50% cattle slurry, 40% cheese whey and 10% of pretreated *Phragmites australis* achieved an OLR of 3.28 g-VS/l-d with a methane yield of 241 l-CH_4/kg-VS. The digestate methane potential with a high OLR in the feed was found equal to 219 l-CH_4/kg-VS.

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Parameter	Cow manure	Cheese Whey	*Phragmites*
pH	6.94	4.12	-
BOD 5 (mgO2/l)	39,000	59,000	-
COD (mgO2/l)	120,000	74,400	-
Density (g/cm^3)	0.97	1	-
105° Residual (%)	11.6	5	98.2
505° Residual (%)	2.5	0.5	3.64
Total Volatile Solid (%)	9.1	4.5	80.9
NH4 (mg/L)	1,400	78	-
Volatile Fatty Acids (mg/l)	0	0	-
Sulfides (H2S) (mg/l)	0	0	-
Alkalinity (meq/l)	140	NA	-
Calorific value (kcal/kg)			3,460

Table 1 Physical and chemical parameters of used biomasses.

Parameter	Outlet mixture 128 l Digester Co-digestion Test	Outlet mixture 128 l Digester DMY Test
pH	7.24	7.75
BOD 5 (mgO2/l)	8,400	1,050
COD (mgO2/l)	52,000	33,000
Density (g/cm^3)	0.97	1
105° Residual (%)	4.8	2.5
505° Residual (%)	1.3	1.2
Total Volatile Solid (%)	3.5	1.4
NH4 (mg/l)	1,100	1,800
Volatile Fatty Acids (mg/l)	0	0
Sulfides (H2S) (mg/l)	0	0
Alkalinity (meq/l)	140	230

Table 2 Physical and chemical parameters of co-digestion test.

Parameter	128 l digester Co-digestion test (Average)	128 l digester DMY test (Average)
OLR (g VS/(l*d))	6.35	1.1
HRT (d)	44	32
Specific bio-methane production (l CH_4/kg VS)	241	219
Biogas quality (%)	54.1	53.6
Biogas yield (l/kg VS)	445	407
Electricity (kWh t/d)	2.9	0.9
Bio-methane Yield (BMY_1)	78	

Table 3 Comparison of main process parameters.

Parameter	128 l digester Co-digestion test (Average)	128 l digester DMY test (Average)
Methane (CH_4) (%V/V)	54.1	53.6
Carbon dioxide (CO_2) (%V/V)	44.9	45.6
Oxygen (O_2) (%V/V)	0.1	0
Carbon monoxide (CO) (ppm)	615.1	287
Hydrogen sulphide (H_2S) (ppm)	362.5	215

Table 4 Biogas average parameters for the conducted experiment.

Parameter	128 l digester Co-digestion test (Average)	128 l digester DMY test (Average)
HRT (d)	44	32
COD feeded (g/l)	110	52
OLR (g)	137.5	89.3
COD reduction (%)	52.7	36.5

Table 5 COD behaviour during the experiment.

Figures caption:

Figure 1: Details of the own made experimental 128 L anaerobic digestor used in the test.

Figure 2: Morgex hybrid phytoremediation plant general layout with details of functional blocks.

Figure 3: Process performance during anaerobic startup, co-digestion and digestate methane yield test inside the 128 l digester. The cumulative curve indicates the biogas production during the whole test and the biogas quality curve shows the methane percentage inside the produced biogas.

Figure 4: a) daily biogas production during the startup test; b) during the co-digestion test; c) during the DMY test.

430 *Figure 1*

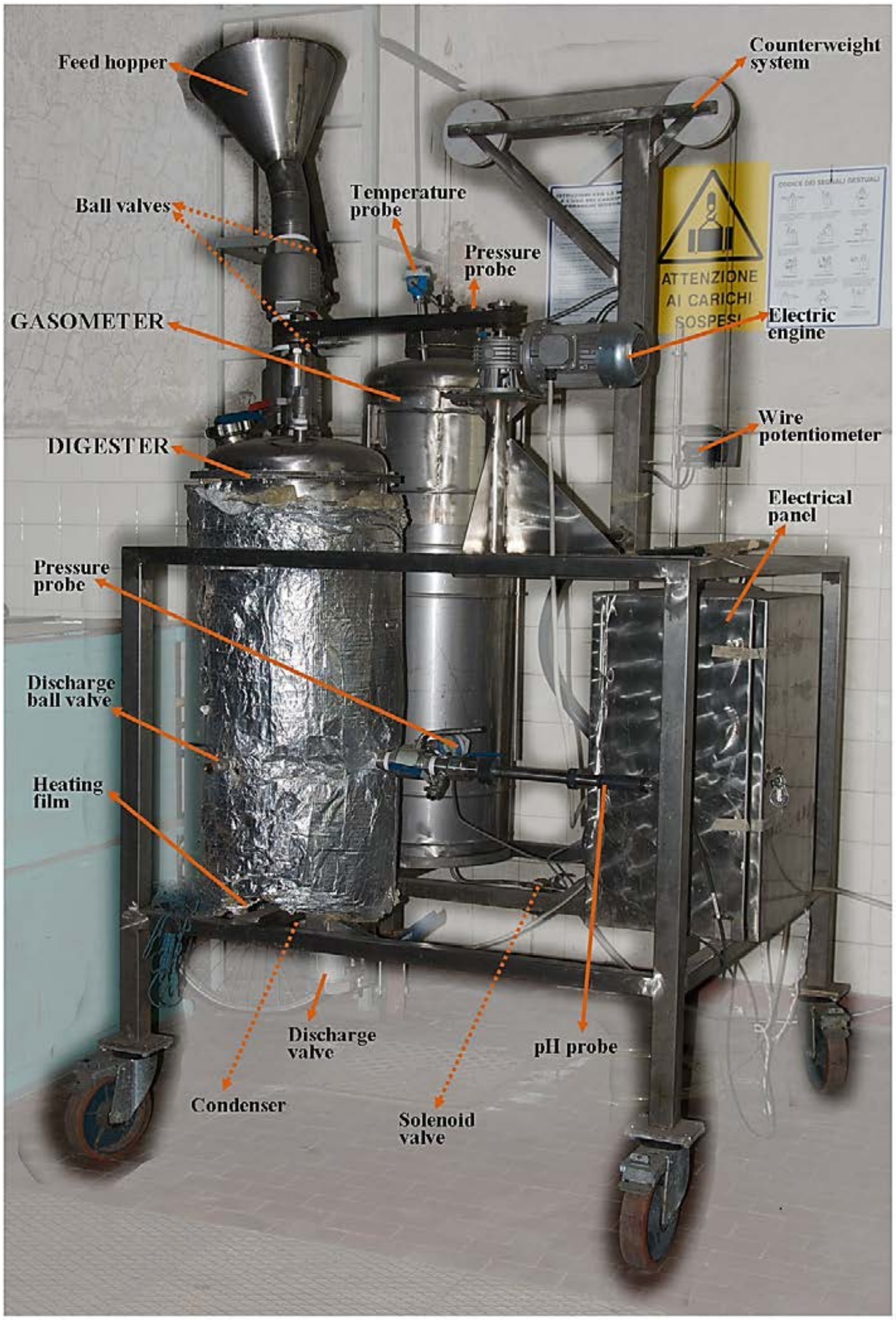

Feed hopper
Counterweight system
Ball valves
Temperature probe
Pressure probe
GASOMETER
ATTENZIONE
AI CARICHI
SOSPESI
Electric engine
Wire potentiometer
DIGESTER
Electrical panel
Pressure probe
Discharge ball valve
Heating film
Discharge valve
pH probe
Condenser
Solenoid valve

Figure 2

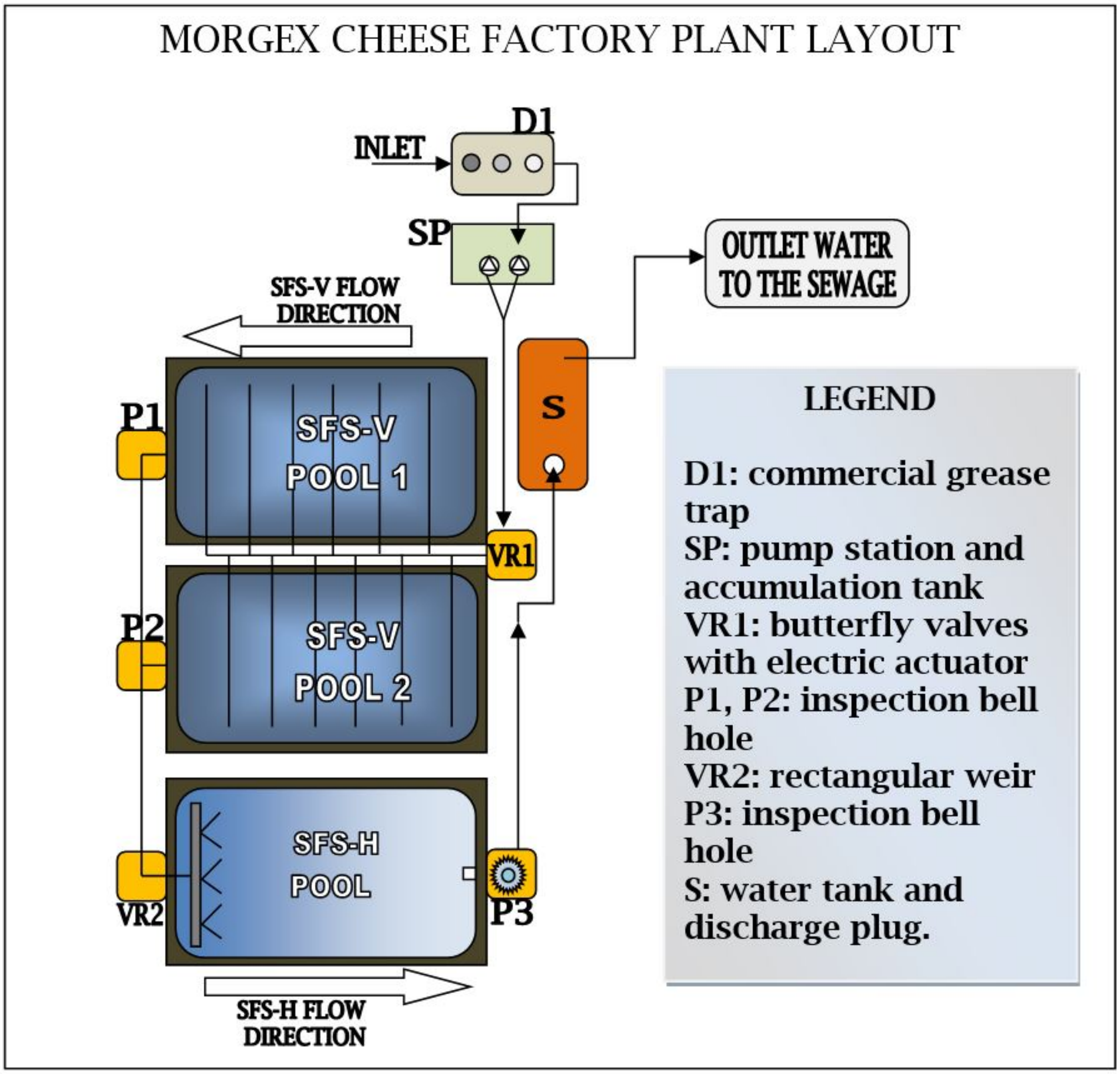

MORGEX CHEESE FACTORY PLANT LAYOUT
D1
INLET
SP
OUTLET WATER TO THE SEWAGE
SFS-V FLOW DIRECTION
S
P1
SFS-V POOL 1
VR1
P2
SFS-V POOL 2
SFS-H POOL
VR2
P3
SFS-H FLOW DIRECTION
LEGEND
D1: commercial grease trap
SP: pump station and accumulation tank
VR1: butterfly valves with electric actuator
P1, P2: inspection bell hole
VR2: rectangular weir
P3: inspection bell hole
S: water tank and discharge plug.

Figure 3

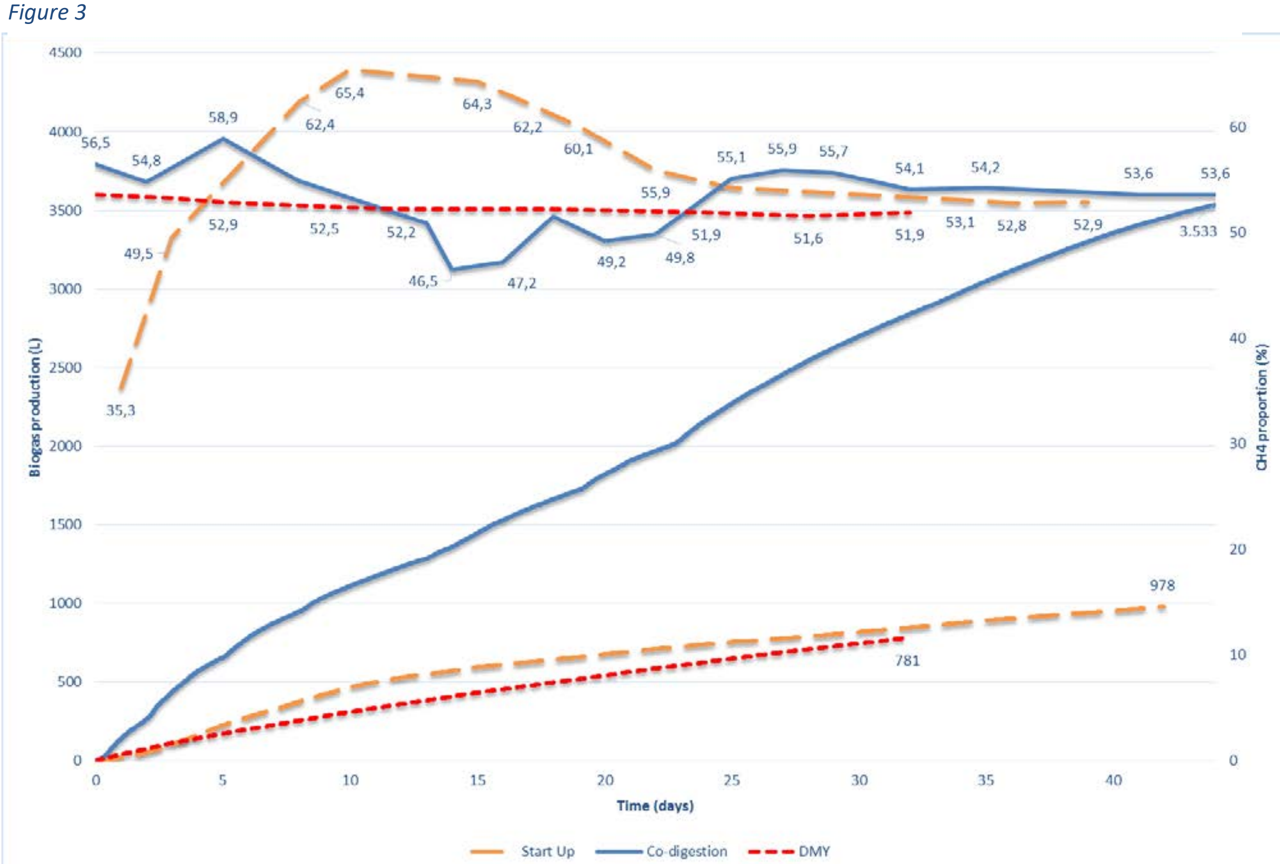
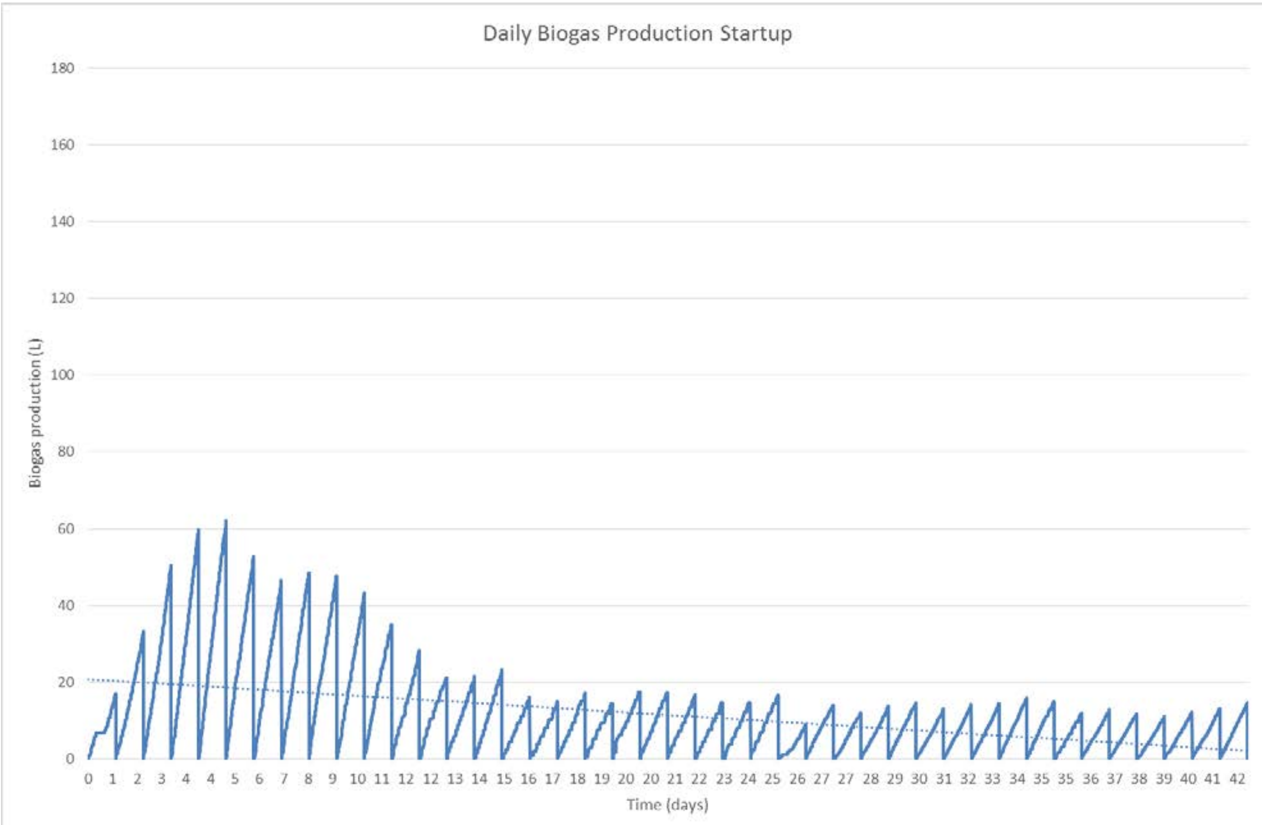

Biogas production (L)
CH4 proportion (%)
Time (days)
Start Up
Co-digestion
DMY
56,5
54,8
58,9
65,4
64,3
62,4
62,2
60,1
55,9
55,1
55,9
55,7
54,1
54,2
53,6
53,6
52,9
52,5
52,2
49,5
46,5
47,2
49,2
49,8
51,9
51,6
51,9
53,1
52,8
52,9
3.533
35,3
978
781

Figure 4a



Daily Biogas Production Startup
Biogas production (L)
0
20
40
60
80
100
120
140
160
180
0 1 2 3 4 4 5 6 7 8 9 10 11 12 12 13 14 15 16 17 18 19 20 20 21 22 23 24 25 26 27 27 28 29 30 31 32 33 34 35 35 36 37 38 39 40 41 42
Time (days)

Figure 4b

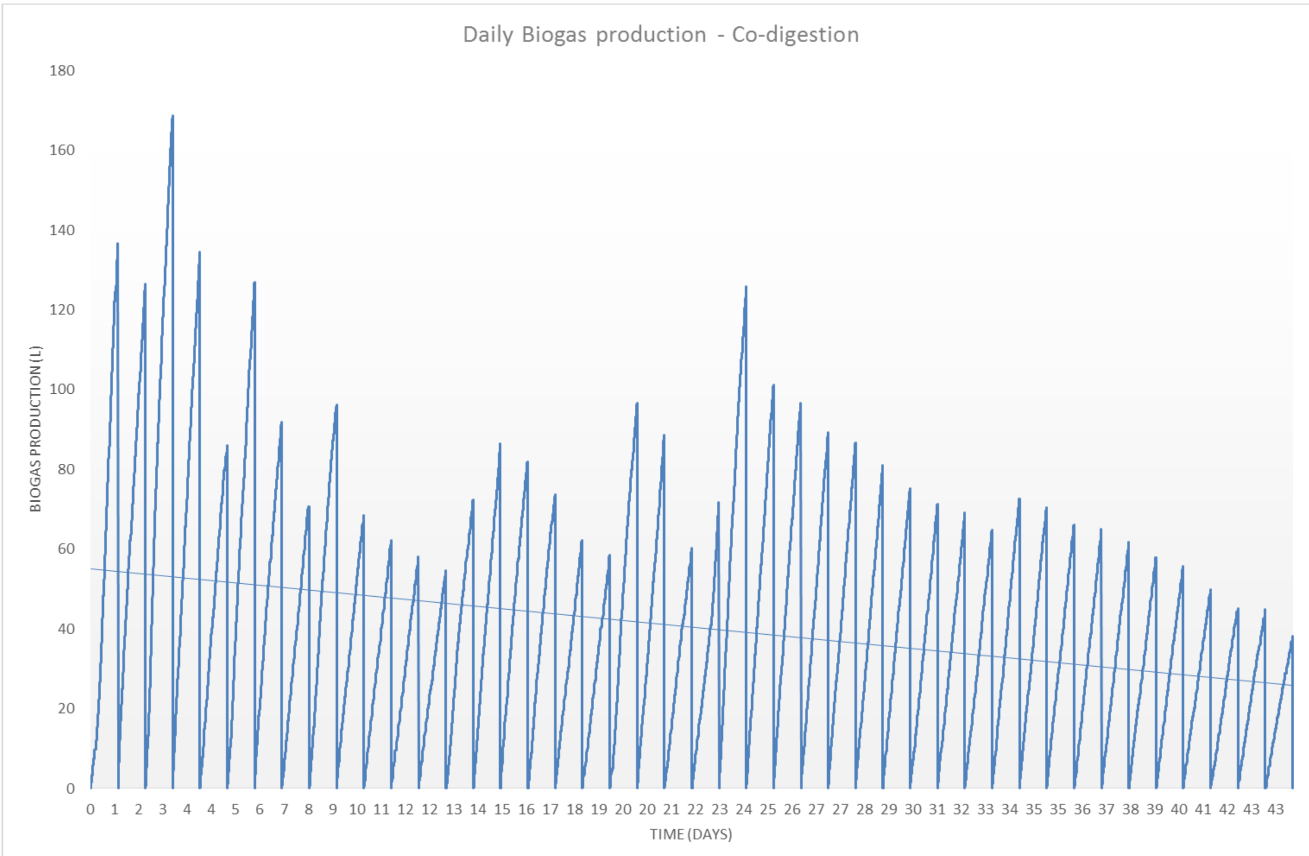
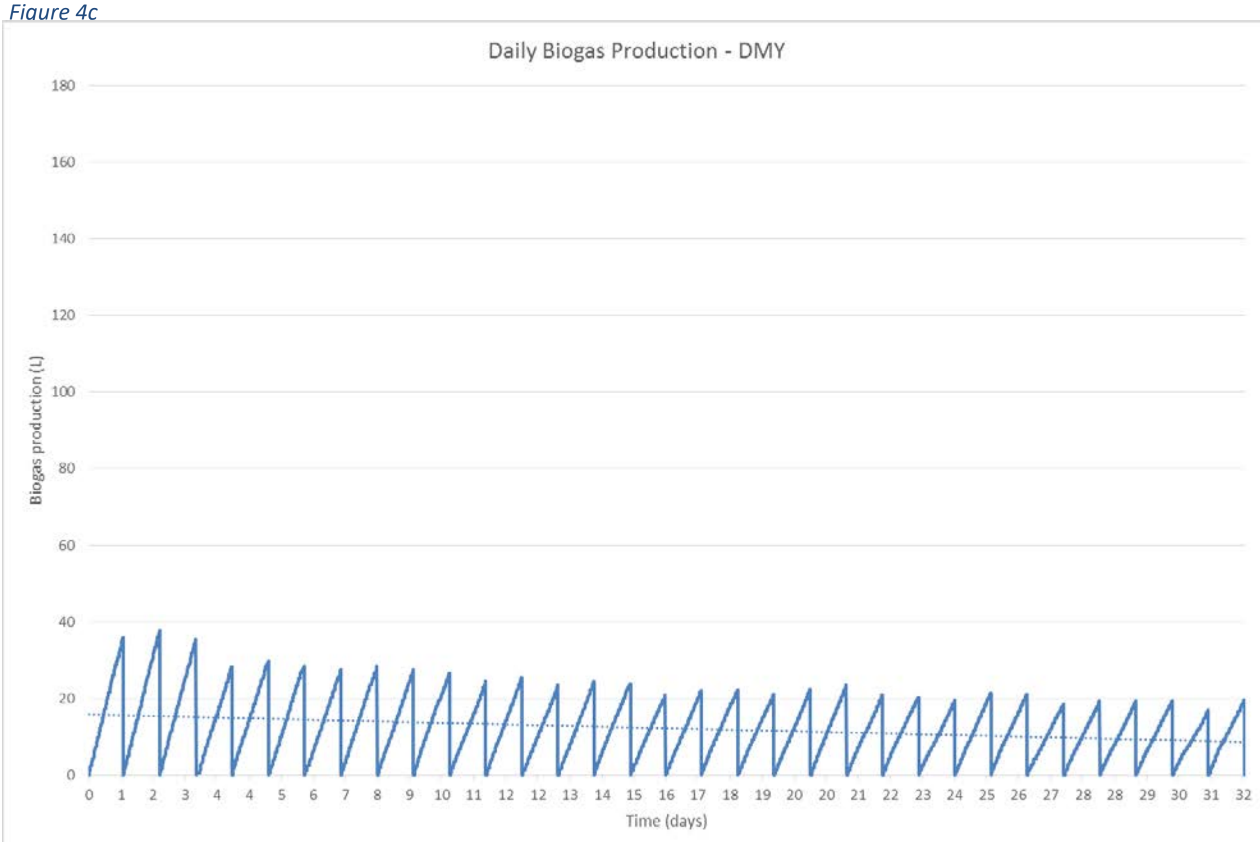

Daily Biogas production - Co-digestion
BIOGAS PRODUCTION (L)
0
20
40
60
80
100
120
140
160
180
0 1 2 3 4 4 5 6 7 8 9 10 11 12 12 13 14 15 16 17 18 19 20 20 21 22 23 24 25 26 27 27 28 29 30 31 32 33 34 35 35 36 37 38 39 40 41 42 43 43
TIME (DAYS)

Figure 4c


Daily Biogas Production - DMY
Biogas production (L)
180
160
140
120
100
80
60
40
20
0
0 1 2 3 4 4 5 6 7 8 9 10 11 12 12 13 14 15 16 17 18 19 20 20 21 22 23 24 25 26 27 28 28 29 30 31 32
Time (days)