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

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1 *Above ground part of common reed to enhance anaerobic co-digestion of farm*
2 *biomasses: potential, monitoring and efficiency.*

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6 Abstract

7   This paper shows that common reeds used in phytoremediation plants can

8 successfully disposed of in anaerobic digestion reactors. At mesophilic condition the

9 following were investigated: biogas yield resulting from an anaerobic co-digestion campaign

10 of mixtures of cattle slurry, cheese whey and aboveground biomass of *Phragmites australis*,

11 rates of production of methane, removal efficiencies of chemical oxygen demand (COD) and

12 bio-methane yield (BMY). The resulting concentration of methane in the biogas was between

13 53-56%. Maximum removal efficiencies for COD was 70%. The mixture of 50% cattle

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14 slurry, 40% cheese whey and 10% of aboveground parts of *Phragmites australis* achieved an

15 Organic Loading Rate (OLR) of 3.3 g-VS/l-d with a methane yield of 241 l-CH_4/kg-VS. A

16 high digestate methane potential with a high OLR in the feed was also tested, with a result

17 of 219 l-CH_4/kg-VS.

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

20

21   1. Introduction

22   EEC Directive 91/271, concerning urban and industrial wastewater, rules that the

23 wastewater produced from farming and industrial production must now be subjected to

24 treatment. A low cost solution are phytoremediation systems that are becoming widely used

25 for the treatment of wastewater. The vegetal species used in most of these systems are part

26 of the common reed family. The common reed is currently the most frequently used plant

27 inside phytoremediation systems. They are also one of the most widespread vascular plants

28 on Earth and are one of the dominant plants in Europe. *Phragmites australis* is a macrophyte

29 often used to phytoremediate wastewater coming from urban sewage, but more frequently,

30 from farming and its aboveground parts are generally cut twice a year.

31   To date, research has focused mainly on the strategies used in the big scale management

32 of these plants (Hanssons et al, 2004, Kuhlman et al., 2013 and Risén et al., 2013). Showed

33   that the aboveground parts of the common reed can be used to produce bio-methane.

34   However, very little research has been carried out with regard to anaerobic co-digestion

35   (A.D.). A productive final destination for the aboveground parts of common reed have been

36   studied by Risén et al. (2013). This allows mixing different kinds of biomasses that need to

37   be treated before disposal. The co-digestion of different kinds of biomass brings the

38   Carbon:Nitrogen ratio into the optimal range, indicated in 20/1 – 30/1 by Parkin and Owen

39   (1986), 10/1 – 30/1 by Schattauer and Weiland (2004), but also enhances the biomethane

40   yield.

41   This paper reports on a study of enhancement of common reed co-digestion. C:N ratio high

42   value influences CH4 production as the carbon cannot optimally be converted to CH4. The

43   low values obtained for C:N ratio implies that the feedstock could result in a high total

44   ammonia nitrogen (TAN) release and a high volatile fatty acids (VFAs) accumulation inside

45   the digester (e.g. cattle slurry and whey co-digestion). As demonstrated by Parkin and Owen

46   (1986) both TAN and VFAs are fundamental intermediates and potential inhibitors in the

47   anaerobic digestion process. A working method to avoid excessive ammonia accumulation

48   is to adjust low feedstock C:N ratios by adding high carbon content materials such as the

49   aboveground biomass of *Phragmites australis*. Several examples of anaerobic co-digestion

50   of different substrates can be found in scientific literature. Sosnowaki et al. (2003) studied

51   the co-digestion of sewage sludge and municipal solid waste (MSW). Callaghan et al. (2002)

52   investigated co-digestion of cattle manure/slurry with different kinds of fruit, vegetable

53   wastes and chicken manures. In both cases successful blending of high C:N and low C:N

54   feedstock improve digester performance and bring the following benefits of co-digestion:

55   dilution of potentially toxic ammonia, allowing for an increased loading rate and an improved

56   biogas yield.

57   The present study investigated the feasibility of anaerobic co-digestion of a previously

58   tested mixture (cow manure and whey) with the addition of aboveground parts of *Phragmites*

59   *australis* let out from a phytoremediation plant that treats cheese factory wastewater. The

60   purpose was to investigate how an important variation in the feeding mixture can affect the

61   methane production during co-digestion. The quality criteria for anaerobic digestion of

62   selected substrates were established, and the suitability of *Phragmites australis* in the co-

63   digestion and achievable methane yields was determined. Furthermore, the digestate methane

64   yield potential was evaluated, as well as the Chemical Oxygen Demand (COD) removal

65   efficiencies, and energy assessments were performed.

66   A full scale AD process produces unstable digestate and considerable biogas can be

67   obtained. An investigation was therefore performed to compare this residual biogas potential

68   (BMP) with the measurement of the initial biogas potential (BMP of the feeding materials).

69 This investigation helped to evaluate the full-scale AD process. An experimental campaign

70 was conducted using a Continuous Stirred Tank Reactor of 128 L under standard temperature

71 and pressure conditions (STP). Two benefits were obtained: first, the *Phragmites australis*

72 used for the replacement of the cheese whey was derived from a phytoremediation plant

73 treating its biomass. Second, an addition of carbon inside the substrate brought a more

74 optimal C:N ratio.

75

76   2. Materials and methods

77   A pilot scale anaerobic digester was used for conducting the test. It had the following

78 principal components: anaerobic reactor, gasometer and feed chamber. The size of the reactor

79 was not relevant in the evaluation of the methane yield as this parameter was calculated under

80 Standard Temperature and Pressure (STP) and expressed as CH_4 liter/kilograms of volatile

81 solids. The only related variable was the quantity of volatile solids inserted inside the reactor.

82

83   2.1 Pilot device

84   The reactor covered a surface of 1.20 m^2, was 2.30 m height (Fig. 1). The reactor had a 316

85 stainless steel tank realized by a cylinder 90 cm high with a diameter of 40.3 cm, closed by

86 two caps on the top and on the bottom, for a total volume of 128 l and a working volume of

87   about 100 l. It was equipped by a mixer system with a blade propeller and a scraper on the

88   bottom, both 316 stainless steel made and activated by a variable speed electric engine

89   controlled by an inverter. The digester and the gasometer were equipped with a complete

90   probe monitoring system including: a temperature probe inserted on one side of the reactor;

91   a temperature and a pressure probes on the gas holder; a pH probe inserted inside the digester.

92   The temperature was automatically controlled to remain inside mesophilic range and it was

93   regulated by an electrical resistance (15 m). It was wrapped around the reactor and covered

94   with insulating film to maintain the temperature near 35°C. The system was equipped with a

95   small tank to collect condense, designed to be emptied automatically. The indirect measure

96   of biogas yield was obtained with the movement of a slide-wired potentiometer, which was

97   linked from one side with the gasometer upper parts and fixed with the chassis from the other.

98   The operational pressure was about 9-10 mBar. The outlet pipe was equipped with a solenoid

99   valve activated by a relay to allow the automatic discharge of the produced biogas. This

100   system was described in details and used in a previous experience (Comino et al., 2012).

101

102   2.2 Phytoremediation plant

103   The constructed wetland for the diary "Laiterie Cooperative Valdigne" in Morgex (Valle

104   d'Aosta, Italy) was built both to respect the environmental resources and to give a contribute

105   to the development of such technology. It consists on a fat-removal unit and a basin for the

106   storage and the distribution of the wastewater which precede three pythoremediation beds

107   (Fig. 2): the first two are parallel and they work as submerged vertical flow wetland with

108   gravel medium for a total area of 180 m^2, the last is a submerged horizontal flow wetland

109   with sand medium and a total area of 360 m^2. These beds are planted with *Phragmites*

110   *Australis* (CAV.) *Trin. Ex Steud*., with a density of about 4 plants/m^2. At the time of the

111   biomass harvest, the system is two years old. Deep description, system efficiencies and

112   inlet/outlet wastewater analysis of the constructed wetland were already presented in a

113   dedicated work (Comino et al., 2011).

114

115   2.3 Feed material

116   The feed biomass used for the realization of the two campaigns was composed of cow

117   manure, cheese whey and the aboveground parts of *Phragmites australis*. The cow manure

118   and the fresh cheese whey were both collected at the livestock farm "Fontanacervo" located

119   in Villastellone (Turin – Italy). The collected biomass that was not immediately used to fill

120   the reactors for the startup phase, was stored inside a refrigerator at about 4°C. The

121   aboveground parts of *Phragmites australis* (almost 7 kg of fresh biomass) was collected from

122   the phytoremediation plant described above and stored inside a 50 L barrel. The *Phragmites*

123   biomass was first spread on a large surface and dried on a thin layer for 24 h at about 60°C.

124   Then it was chopped into a smaller size of about 2 mm (Mshandete et al. 2006). The volatile

125   solids were equal to 9.1 % in the cow manure, 4.5% in the cheese whey and 81% in the dried

126   *Phragmites*; BOD_5 values were obtained for cow manure and cheese whey and were equal to

127   39,000 mg/l, 59,000 mg/l, the COD were equal to 120,000 mg/l, 74,400 mg/l respectively.

128   The influent and effluent details are presented in Table 1 and Table 2.

129

130   2.4 Startup tests

131   The reactor was initially filled with only cattle slurry to obtain a stable anaerobic digestion

132   under batch feeding conditions. About 80 kg were used for the scaled-up device. During the

133   startup phase it is important to fill in with only cattle slurry the reactor to avoid the risk of a

134   process collapse due to the whey trend to acidify very rapidly (Comino et al. 2012). Startup

135   tests lasted 42 days. The substrate was stirred every 2 days for 30 min and the produced

136   biogas was analyzed to monitor the quality.

137

138   2.5 Co-digestion test

139   After the startup phase co-digestion of test mixture was started. The feeding ratio was

140   implemented as follow: the total processed quantity was equal to 55 kg of mixture (50%

141 cattle slurry, 40% cheese whey and 10% *Phragmites australis*). The slight differences

142 between the startup quantity (80 Kg) and the co-digestion one (55 Kg) was due to facilitate

143 the loading/unloading operations. So the first step was to reduce the total volume inside the

144 anaerobic reactor from 80 to 55 Kg. Then the co-digestion feeding strategy was adopted and

145 about 5 kg of substrate was removed and a 5 kg mixture (2.5 kg of manure, 2 kg of cheese

146 whey and 0.5 kg of Phragmites australis) was loaded inside the reactor. Each test lasted 34

147 days of fed-batch feeding, plus a week of anaerobic rest with no feeding (batch condition).

148 Feeding of the reactor was done 3 times a week until the complete replacement of the initial

149 biomass. Such as was observed in past experience no purging with nitrogen was necessary.

150 It was observed that less than 1% oxygen in the reactor volume did not adversely affect the

151 test. The probes inside the system were calibrated before the beginning of the test. The gas

152 production was checked at least twice a day via remote control. For the campaign the

153 demonstrated different mixing intensity effect (Kaparaju et al. 2008), and the consequence

154 of particle size on biogas yield (Mshandete et al. 2006) were taken in consideration. The

155 substrate was stirred every time a feeding operation was performed for about 30-45 min. The

156 temperature inside the reactor was always maintained at 35.5 °C ± 0.5. Between one feed and

157 the other no stirring was performed inside the reactor. The gasometer was equipped with

158 electronic controlled electro valves that allowed biogas discharge when reached pre-

159 established values. pH, temperatures, pressure and gasometer vertical movements were all

160 monitored at 5-min intervals. After the last feed, the system was left undisturbed for almost

161 7 days to evaluate biogas production stabilization. Substrate samples for the chemical

162 analysis were collected at the end of the test (Tab. 2).

163

164 2.6 Digestate methane yield tests (DMY)

165 After the co-digestion was started a monitoring test without discharge of any biomass from

166 the previous one. Indeed it was expected that the digestate still contain a considerable amount

167 of undigested organic matter with a high OLR and a relatively short HRT. The substrates

168 were stirred every two days for 45-min when biogas samples were collected. Main systems

169 parameters were constantly checked including methane concentration inside the biogas. The

170 anaerobic reactor remained sealed during the experimentation period. After 32 days of

171 retention, the test was concluded and samples collected for chemical analysis (Tab. 2).

172

173 2.7 Bio-methane yield

174 To allow direct comparison with full-scale plants the bio-methane yield (BMY_1) of the co-

175 digestion test was determinate, by using the following equation presented by Schievano et al.

176 (2011):

177
$$BMY_1(\%) = \frac{BMP_{in}*TS_{in} - BMP_{out}*TS_{out}}{BMP_{in}*TS_{in}} * 100; \qquad (1)$$

178

179   Where BMP_{in} is the bio-methane potential in the fed mixture, BMP_{out} is the bio-methane

180   potential in the output digestate, TS_{in} are the total solids fed during the observed period and

181   TS_{out} are the total solids output with digestate during observed period. The BMY_1 obtained

182   with Eq. (1), can be compared to the effective specific methane produced (SMP) in a full-

183   scale plants and calculated with the following equation:

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

185

186   2.7 Chemical analysis and procedures

187   The feed materials and obtained digestate were stored at 4 °C immediately after sampling.

188   Chemical analyses were performed within 48 h in an accredited laboratory. BOD_5 was

189   analyzed with the IRSA-CNR n°. 5100 A/94 method; COD with the IRSA-CNR n°. 5110/94

190   method; pH samples with IRSA-CNR Quad 100 method 2080/94 and inside the reactors with

191   pH probes. Density was evaluated with the EMRO/012/1999 method; 105 °C residual, and

192   the 550°C residual as the Total Volatile Solids were obtained with the IRSA-CNR Quad. 64

193   n°. 2.4.2/84 method. Ammonia was evaluated following the IRSA/APAT guidelines 29/2003

194   method n°. 4030C. Volatile Fatty Acids (C1-C6) were measured with the EMGC 003/1999

195   method. The *Phragmites australis* calorific value was calculated according to the ASTM D

196   240 method. A GA-2000 gas analyzer was used for the real time biogas monitoring. The

197   monitored parameters were CH_4, CO_2, O_2, CO and H_2S, as well barometric pressure and

198   relative pressure inside the gasometer. Organic loading rate (OLR) and hydraulic retention

199   time (HRT) were calculated based on the regular additions. The data collected by the data

200   logger were analyzed at the end of each test and processed using an own made database to

201   evaluate different analytic parameters.

202

203   3 Results and discussion

204   3.1 Startup test

205   During the first 42 days, limited biogas production can be observed (Fig. 3). The pH value,

206   which is not shown, increased in the first 2 days from about 6.9 to 7.8. This behavior

207   anticipated an increase in biogas production which then reached a maximum between days 4

208   and 6 and then stabilized (Fig. 4a). A total of about 979 l of biogas was produced (Fig. 3).

209   Considering that CH_4 inside the biogas was 55.4% the total amount of produced methane was

210   543 l. Following the methodology to obtain the specific bio-methane productions on VS basis

211   with a total of 3.088 kg of VS inserted in the reactor was obtained a 174.8 l-CH4/kg-VS for

212   42 days of active anaerobic digestion. The startup followed the expected behavior and trend

213   of biogas production from cattle manure. Similar values were found by Amon et al. (2007),

214   Brachtl (2000), Thomè-Kozmiensky (1995) and Comino (2010, 2012). The ranges for the

215   production of biogas, cited above, are all similar to what was obtained during the startup,

216   which was 317.03 l-biogas/kg-VS.

217

218   3.1 Co-digestion tests

219   The use of a biomass mixture with 50% cheese whey and 50% cattle manure was proved

220   suitable and effective to produce methane (Comino et al. 2012). The addition of aboveground

221   biomass of *Phragmites australis*, to this mixture, allows to evaluate if a reduction of whey

222   could change biogas production in quality and quantity. The different composition inside the

223   substrates shows the methane yield at increasing OLR.

224   After a start-up phase with an OLR established inside the optimal range at about 0.9 g-

225   VS/l-d, the test investigated the scaled-up reactor behavior using an OLR values equal to

226   3.28 g-VS/l-d (Tab. 3). The pH monitoring showed very smooth fluctuation during the test,

227   the periodic unloading/loading operations were not clearly visible. The biogas production is

228   presented in Figure 3 and the daily biogas production in Figure 4b. The final rest period of

229   about a week showed a very smooth and progressive reduction of biogas production rate. No

230   accumulation of undegraded material was observed inside the digester. The methane

231   proportion inside the produced biogas with the scaled-up reactor (50% cattle slurry, 40%

232   whey and 10% *Phragmites*) had an average value of 54.1%, a maximum value of 58.9% and

233   a minimum of 46.5% (Fig. 3). It started to stabilize at the end of the test, while during the

234   most part of the experiment followed a performance related to the feed operation. The

235   obtained methane yield was equal to 241 l-CH_4/kg-VS with an OLR of 3.28 g-VS/l-d. In

236   terms of COD were found the following values equal to 110 g/l, OLR= 137.5 g, COD/l_R and

237   HRT=44 days. As visible in Fig. 3 the reactor continued to produce biogas smoothly, the

238   total produced volume was equal to 3534.8 l with a COD reduction of 53% (Tab. 5).

239

240   3.3 Digestate Methane Yield (DMY) tests

241   To confirm the data obtained during the campaign was taken in consideration the

242   realization of a theoretical methane yield, but it will bring a series of uncertainties that will

243   be very difficult to discuss. The model originally developed by Buswell and Boruff (1932),

244   that is able to estimates theoretical methane concentration starting from the chemical

245   composition of organic substrate (C, H, N and S), do not integrate the influence of lignin and

246   assume a total transformation of the element in CH_4 (that is not true under real conditions).

247   Also, carbon content of a feed material can be used in combination with Buswell's equation

248   to estimate methane production, but it is necessary to assume what proportion of the feed

249   material is degraded in the process and in this case, with a mix of three different materials, it

250   will be very difficult to evaluate a real value. Another issue was the fact that a good model

251   needs a detailed database as input factors, and this was not the case as the used materials and

252   mix ratios were used for the first time. For all these reasons it was preferred to realize a

253   Digestate Methane Yield (DMY) test after the experiment, in this way was possible to

254   estimate the residual biogas/methane potential. A tests with a batch-fed regime was

255   performed, as described in paragraph 2.5, after the co-digestion one.

256   The test was carried out after the co-digestion with 50:40:10 mixture, an estimated OLR of

257   about 1.1 g-VS/l-d, that produced a total quantity of biogas equal to 782.7 l. Considering a

258   CH_4 proportion of 53.6%, this amount corresponded to 419,8 l of methane (Fig. 3). The

259   digestate methane yield was 218.9 l-CH_4/kg-VS with a VS estimated value of 1.9 kg,

260   obtained from the chemical analysis taken at the end of the co-digestion test. This value

261   indicates that the digestate potential is very high, but, as visible in Figure 4c, the daily

262   production is steady. In a real scale process digestate can yield an important amount of biogas

263   that could be used to produce electricity (i.e. 0.9 kWh per t/d with the above values). Data in

264   literature shown that the methane yields obtained by several studies are sensible lower than

265   the one presented in this paper (Hansen et al. 2006; Lethomaki et al. 2008; Menardo et al.

266   2011).

267

268   3.4 Discussion

269   No direct comparison can be made with other studies, as this substrate was never tested

270   before, but few experiences were conducted in the past about the digestion of common reed

271   alone or in co-digestion with other organic substrate. Renborg (1984) and Brolin et al. (1988)

272   reported a methane production of 180 l-CH_4/kg-VS conducting a small-scale studies using

273   summer harvested reed. Risén et al. (2013) realized a test using two 30L CSTR digesters

274   with an operating temperature of 52°C and 24 days of HRT. The substrate was a mixture of

275   common reed and   five different fractions of organic material (Slaughterhouse waste – 38%;

276   Cattle manure slurry – 30%; Milk plasma permeate – 15%; Sludge – 12%; Potato residues –

277   5%) obtaining a methane production from reed addition of about 219 l-CH_4/kg-VS. In a test

278   conducted by the authors with pre-treated crop silage and cattle slurry the obtained value was

279   equal to 249 l-CH_4/kg-VS with an OLR of 5.15 g-VS/l-d (Comino et al. 2010). Another

280   experiment conducted with 50% of cattle slurry and 50% of whey had shown a methane yield

281   of 343.4 l-CH_4/kg-VS with an OLR of 2.65 g-VS/l-d (Comino et al. 2012). Few experiments

282   were carried out on co-digestion of cattle slurry and cheese whey. In the past, for these kind

283   of substrates, anaerobic digestion was principally used as a wastewater treatment method,

284   and not considered as a system to produce energy. Lehtomaki et al. (2007) in a study with

285   several energy crops and cow manure mixture, found methane yields between 149 and 268

286   l-CH4/kg-VS. In the high OLR test conducted by Lindorfer et al. (2008) was found methane

287   yields between 360 and 400 l-CH4/kg-VS. A mix of whey and cow manure with a 2:1 ratio

288   was tested successfully by Lo and Liao (1989), they obtained a methane yield equal to 222

289   l-CH4/kg-VS. The presented results show that anaerobic digestion of cattle slurry, cheese

290   whey with *Phragmites australis* could be successfully achieved without the use of chemicals

291   (for pH correction) with a 50:40:10 substrate. As the aboveground part of the *Phragmites*

292   was dry (Table 1) a liquid fraction was required to maintain sufficiently wet the substrate.

293   Normally to compensate this situation the substrate was diluted with water. However, this

294   experiment demonstrated that whey can be used as an ideal substitute for water, as even if

295   contribute to increase the overall COD, the COD reduction in both test campaign were greater

296   than 50%. Whey also contribute to add needed nutrients and vitamins to the microbiota.

297   Other studies with different types of biomass mixture, Stewart (1980) and Jarvis et al.

298   (1997), have observed a maximum OLR of 6.7 kg-TS/m^3-d. Nordberg et al. (2007) have

299   reached a maximum OLR equal to 3 g-VS/l-d in a trial with alfalfa silage that brought to a

300   process breakdown. In past tests a working and productive process with an OLR value equal

301   to 5.15 g-VS/l-d was obtained, but when reached a OLR of 7.78 g-VS/l-d the system rapidly

302   breakdown (Comino et al. 2010). With a high OLR of 6.35 g-VS/l-d the mostly affected

17

303   parameter is the residual methane potential that, as described in the next paragraph, could

304   still remain high.

305   The BMY_1 indicated relatively high efficiency of the lab-scale digester (78%) (Table 3).

306   Observing the daily biogas production (Fig.4b) can be noticed a couple of slight inhibition

307   of the methanogenic activity, occurred between days 10 to 14 and 21 to 24, mainly due to a

308   probably increased lignin content. Johnsson (1986) reported that is important that the reed is

309   not harvested too late in the growing season, since the lignin content will be higher.

310   With the presented result, considering the test conducted with the scaled-up reactor it

311   would be possible to obtain electricity production of about 2.9 kWh per 1 t/d with a CHP

312   technology with a considered efficiency of 36%. This kind of mixture has an energy potential

313   with the same order of magnitude of the energy crop and livestock waste co-digestion. The

314   obtained value is lower if compared to what is possible to obtain with energy crops co-

315   digestion, but the environmental benefits are much higher. Also the use of phytoremediation

316   plants for anaerobic co-digestion is a new possibility that is still not investigated adequately.

317   Different types of species, specifically used for this scope, more optimized mixture of

318   biomass inside the reactor can bring higher electricity production.

319

320

321   4 Conclusion

322   The results of this study show that the co-digestion, without induced pH correction, of

323   typical cheese factory biomasses and a small fraction of *Phragmites australis* coming from

324   a phytoremediation plant, is efficient and effective. A mixture of 50% cattle slurry, 40%

325   cheese whey and 10% of pretreated *Phragmites australis* achieved an OLR of 3.28 g-VS/l-d

326   with a methane yield of 241 l-CH_4/kg-VS. The digestate methane potential with a high OLR

327   in the feed was found equal to 219 l-CH_4/kg-VS.

328

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409

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

410 Table 1 Physical and chemical parameters of used biomasses.
411

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

412 Table 2 Physical and chemical parameters of co-digestion test.
413

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	

414   Table 3 Comparison of main process parameters.

415

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

416   Table 4 Biogas average parameters for the conducted experiment.
417

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

418   Table 5 COD behaviour during the experiment.
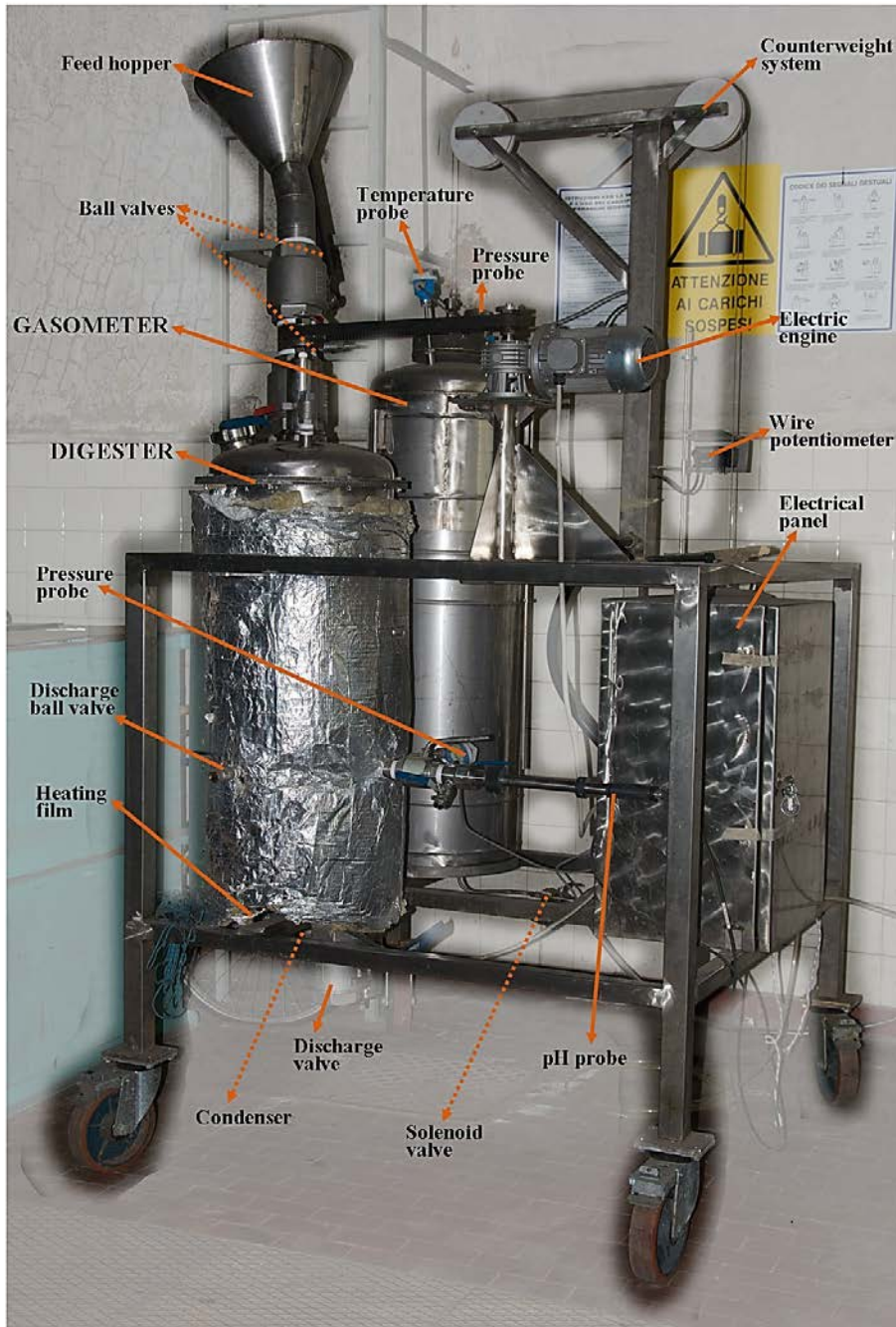
419

420   Figures caption:

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

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

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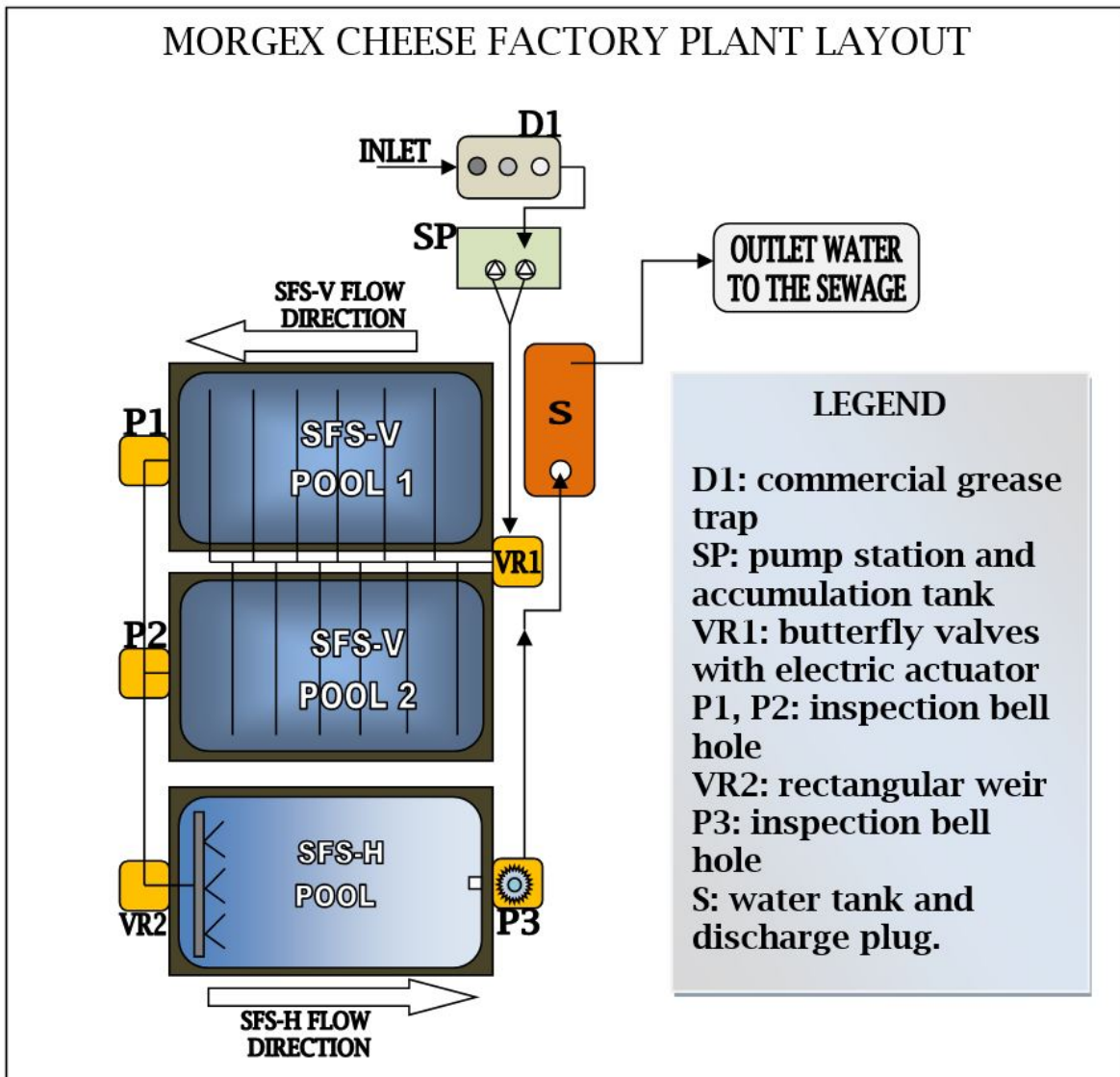427   produced biogas.

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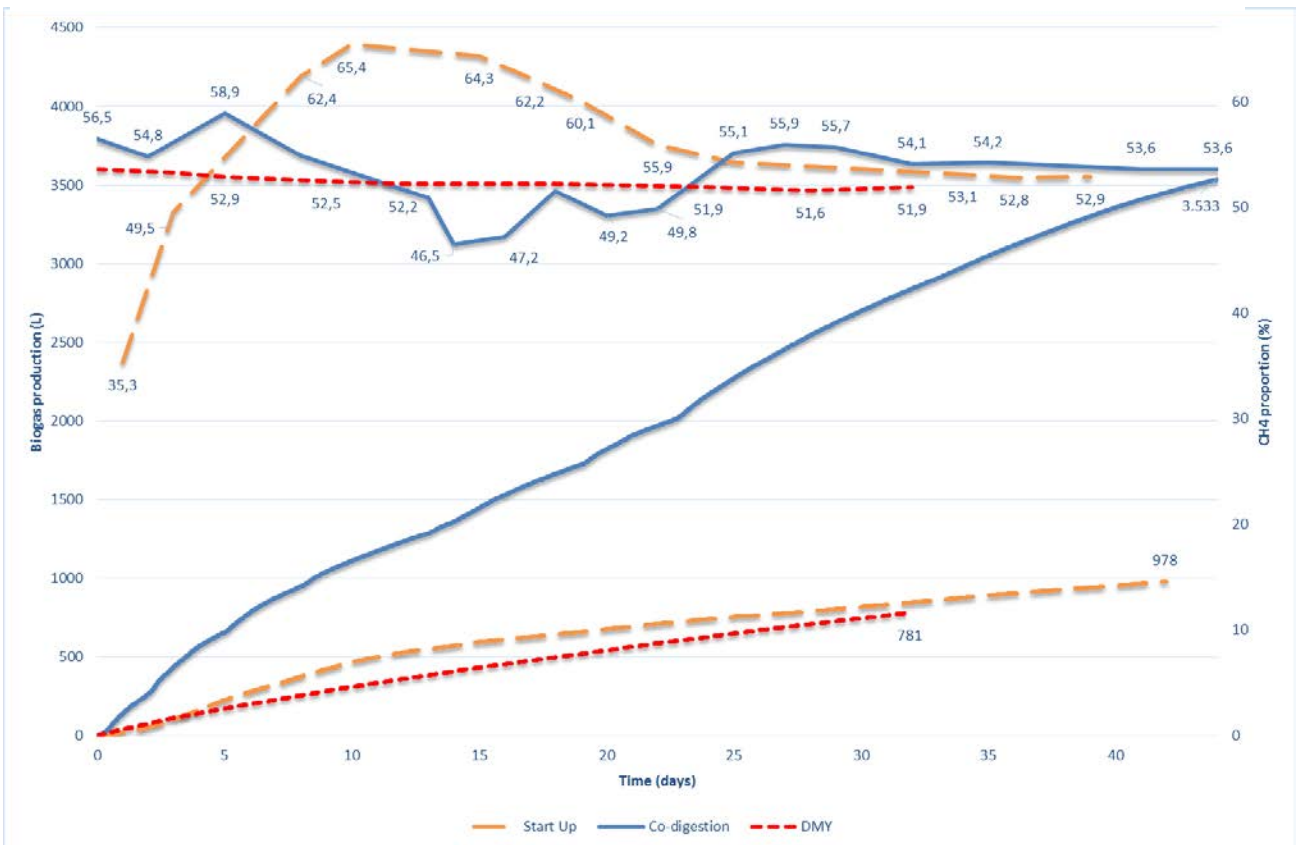429   during the DMY test.

430

431

432 *Figure 2*
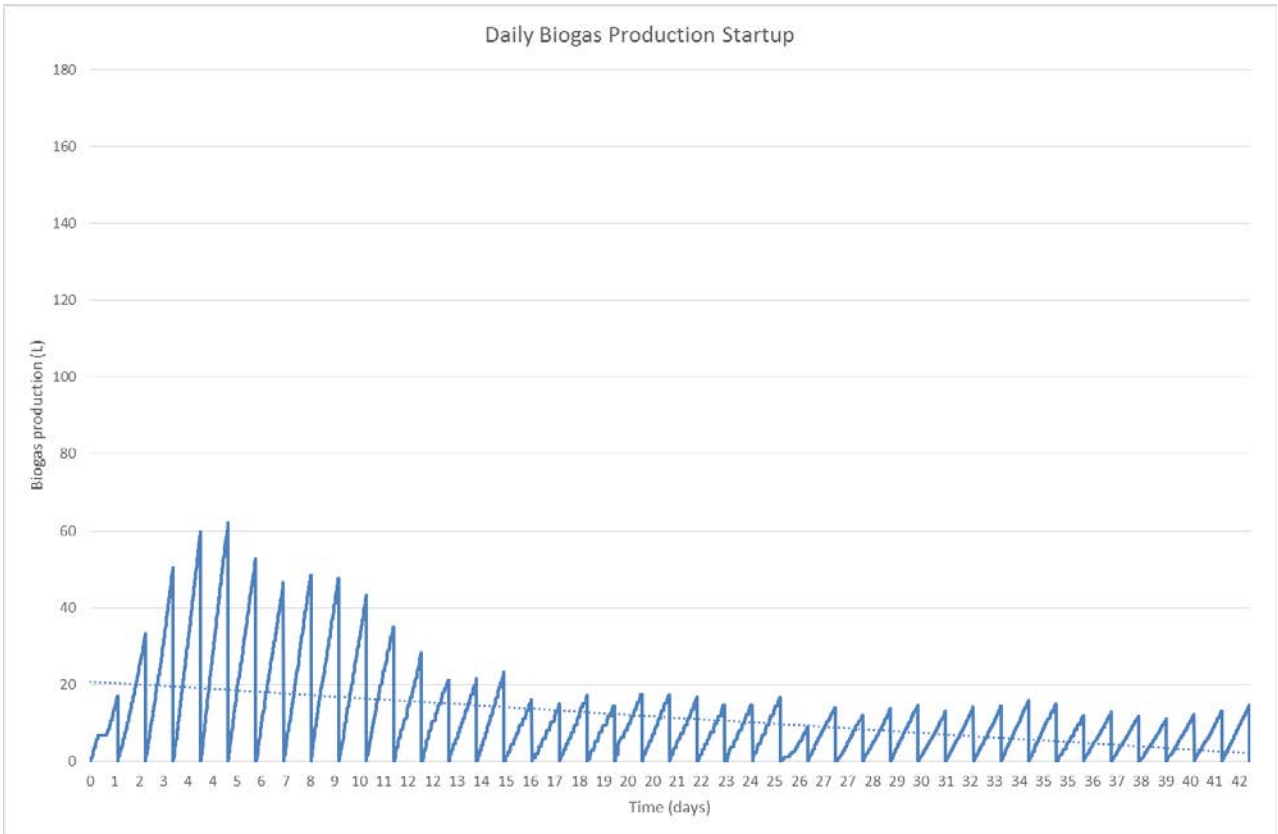

MORGEX CHEESE FACTORY PLANT LAYOUT

INLET

D1

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.

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Figure 3

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Figure 4b

Daily Biogas production - Co-digestion
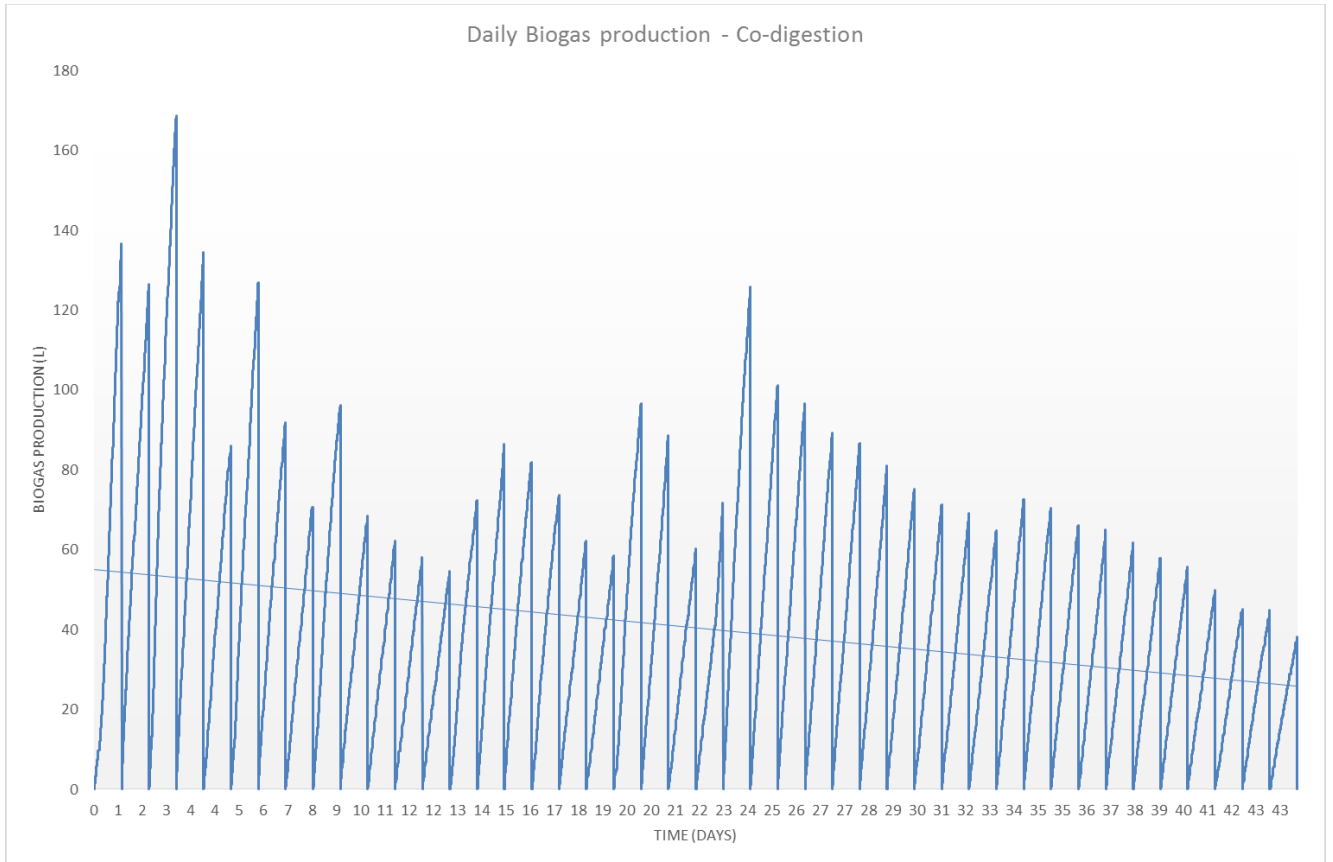
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