Mesophilic and thermophilic anaerobic digestion of the liquid fraction of pressed biowaste for high energy yields recovery

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Abstract

Deep separate collection of the organic fraction of municipal waste generates streams with relatively low content of inert material and good biodegradability. This material can be conveniently treated to recovery both energy and material by means of simplified technologies like screw-press and extruder. In this study, the liquid fraction generated from pressed biowaste from kerbside and door-to-door collection was anaerobically digested in both mesophilic and thermophilic conditions. Continuous operation results obtained both in mesophilic and thermophilic conditions indicated that the anaerobic digestion of pressed biowaste was viable at all operating conditions tested, with the greatest specific gas production of 0.92 $m^3/kgTVS_{fed}$ at an organic loading rate of 4.7 $kgTVS/m^3d$ in thermophilic conditions. The energy returned on energy invested (EROEI) per per ton of biowaste treated is therefore very favorable and around 8.9 $kWh_{produced}/kWh_{consumed}$, demonstrated the viability of this novel configuration with respect to conventional ones.

The contents of heavy metals and pathogens of fed substrate and effluent digestates were analyzed, and results showed low levels (below End-of-Waste 2014 criteria limits) for both the parameters thus indicating the good quality of digestate and its possible use for agronomic purposes.

It was demonstrated that biowaste pressing is a new alternative for mechanical treatment plants that needs to be constructed or revamped.

Key words

Anaerobic digestion, mesophilic, thermophilic, biogas, pressed biowaste, transient conditions

Abbreviations

AD: Anaerobic Digestion, ALK tot: Total Alkalinity, BW: BioWaste, COD: Chemical Oxygen Demand, CSTR: Continuous Stirred Tank Reactor, DW: Dry Weight, EoW: End of Waste, GP: Gas Production, GPR: Gas Production Rate, HRT: Hydraulic Retention Time, MSW: Municipal Solid Waste, OFMSW: Organic Fraction of Municipal Solid Waste, OLR: Organic Loading Rate, Ptot: Total Phosphorus, SGP: Specific Gas Production, SMP: Specific Methane Production, SSC: Steady State Condition, TKN: Total Kjiendhal Nitrogen, TS: Total Solids, TVS: Total Volatile Solids, VFAs: Volatile Fatty Acids, WW: Wet Weight

1. Introduction

Anaerobic digestion is a proven and widespread technology for the management of organic waste of different origin (Mattheeuws and De Baere, 2014). There are currently more than 14,000 plants running in Europe, 28% of which are dedicated to the treatment of wastewater sludge, municipal and industrial organic waste, while the remaining 72% use agro-waste as feedstock (EBA, 2014).

With specific reference to municipal waste management, the success of this technology in recent years has been determined by the implementation of deep separate collection schemes: this determined the possibility of handling streams with a reduced amount of inert material and high moister content and biodegradability like segregated food waste (Valorgas 2010).

Beside anaerobic digestion, the other biological process widely diffused within EU for the management of organic wastes is the aerobic stabilization: at present a compost production of around 10.5 million tonnes of organic waste is reported (COM(2008), 811 http://eur-lex.europa.eu). Noticeably, the two processes, i.e., anaerobic digestion and composting, can be integrated together since the solid fraction of digestate can be treated aerobically (Nayono et al., 2009) so to recovery both renewable energy and nutrients from organic waste. At present some 8 million tons of biowaste are anaerobically digested within EU Countries and normally the biowaste is pre-treated and prepared for the AD process by means of several mechanical steps. A large number of plants treating organic waste started their operations in the 1980s, when both the amount and the composition of biowaste were quite different from the present situation. This has resulted in the need for some modifications both in plant management and operating conditions (Di Maria et al., 2012). In fact results showed that during conventional pre-treatment methods around 30% of the initial wet material could be rejected without any treatment (Pognani et al., 2012). The pre-treatment of the organic fraction of municipal solid waste is in fact one of the main challenges in mechanical–biological treatment plants equipped with anaerobic digesters (Romero-Güiza et al., 2014).

Recent literature highlights the observations related to the loss of biodegradable organic matter during the pre-treatment steps (Muller at al., 1998; Bolzonella et al., 2006; Ponsá et al., 2010b). Moreover, these steps are time and energy consuming (Tonini et al., 2014) and generally are not able to achieve high removal yields for inert materials like small pieces of plastics and heavy materials like crashed glass (e.g., sea shells or similar). These materials could then accumulate inside the reactor determining a reduction of the reaction volume and a possible risk of process failure (Angelidaki and Boe 2010).

Another important aspect to be considered is then the reduction of the energy demand for pre-treatment processes and if possible enhance the biogas production of the anaerobic digestion plants that treat the municipal biowaste (Morais et al., 2007).

In order to address all these issues an interesting option is the use of very simple pre-treatment steps like presses and extruders: in these machines the size of the organic material is reduced while inert material (mainly plastic) is eliminated.

Biowaste pressing, for example, produces of two streams: one semi-liquid to be digested and a second one solid to be composted (Hansen et al., 2007).

Another fundamental aspect related to the treatment of properly pre-treated segregated organic waste is that this results in a digestate or compost of good quality (Bernstad et al., 2013). In fact Regulations in several EU countries only allows for use of compost or liquid fertilizer (digestate) from food waste which is source segregated (as opposed to co-mingled food waste with other waste from a materials recovery facility) to be used in agricultural applications (Browne & Murphy, 2012; Lukehurst et al., 2010).

To avoid this problem, and because of the good quality of biowaste collected by means of door-to-door and kerbside collection schemes, an advanced energy saving pre-treatment approach has been developed: biowaste squeezing. This is a mechanical pre-treatment process. The advantages of mechanical pretreatment include an easy implementation, better dewaterability of the final anaerobic residue and a moderate energy consumption (Ariunbaatar et al., 2014). Pretreatment and digester design are the key techniques for enhanced biogas optimization (Shah et al., 2014).

Only few examples of such approach can be found in literature at the best of our knowledge.

Satoto Nayono et al. (2009) studied AD of pressed off leachate from OFMSW and the co-digestion of press water and food waste (Satoto Nayono et al. 2010) for improvement of biogas production. The co-digestion of press water and food residues with defibred kitchen wastes (food waste), operated at an OLR in the range 14-21 kgCOD/m^3d, reported greater biogas production rates then sole biowaste. An increment of the OLR of biowaste by 10.6% with press liquid fraction increased the biogas production as much as 18%, with a biogas production rate of 4.2 m^3/m^3d at OLR of 13.6 kgCOD/m^3d. These experimentations were conducted through laboratory scale reactors, from 1 to 8 liters working volume.

According to this scenario, and the evidences of recent studies, the aim of the study was to anaerobically digest the liquid fraction of pressed biowaste through a pilot-scale investigation in order to identify bottlenecks, consumes and yields of interest for a possible process up-scale. This research implements initiatives to support of improving the quality of biowaste treated, to enhance energy production and reduce energy costs to manage this bigger and bigger urban stream. It's a new paradigm for biogas plant pre-treatment configuration.

This study deals with a pilot scale trial where biowaste from kerbside collection was mechanically squeezed and the liquid fraction of the pressed material was anaerobically digested. Both mesophilic and thermophilic conditions were tested, applying different organic loading rates, in order to verify the capability of the systems to cope with transient conditions.

Beside the operational parameters and yields, the digestate characteristics were considered in detail also in order to respond to the requirements defined in the "End of Waste Criteria" technical proposal by the Joint Research Center of Sevilla (2014). Based on suggested criteria, pathogens and metals in the digestates were analyzed in order to evaluate the necessity of further anaerobic digestate treatment, for example in a co-composting process.

2. Materials and Methods

2.1 Pretreatment strategy and experimental set up description

A pilot-scale press, specifically designed for this experimentation, was used in order to pre-treat separately collected biowaste and split it into two streams, one liquid to be anaerobically digested and a second one solid to be composted.

Door-to-door collected biowaste from Treviso area (Italy) was first shredded into a knife mill and treated in a press for solid-liquid separation. Only the liquid fraction was then sent to the anaerobic process while the semi-solid part, characterized by a higher content of dry matter, was suitable for aerobic stabilization process as composting.

The semi-liquid stream was then sent to two pilot scale CSTR anaerobic digesters, one mesophilic (37°C ± 0.1) and the other thermophilic (55°C ± 0.1), working with an organic loading rate in the range 3 - 6 kgTVS/m^3_r per day and a hydraulic retention time of 20 days to simulate the best operating conditions expected at a full-scale treatment plant. Organic matter degradation at increasing OLR and ultimately decreasing also the HRT was investigated. The research was carried out using two pilot scale reactors completely equal in terms of electro-mechanics, working volume (0.23 m^3) and heating system. The reactors were made of stainless steel AISI-304 and the mixing was ensured by mechanical anchor-bars agitators in order to maximize the mixing degree inside the reactor, thus avoiding the typical stratification of floating materials on the top and of sinking heaviest materials on the bottom of the reactor. The temperature of 37 °C (mesophilic thermal range) and 55 °C (thermophilic thermal range) of the reactors was maintained constant by an external jacket, in which heated water was recirculated. The biogas produced was sent to a hydraulic guard with the purpose of maintaining an operating pressure of 0.1 m water column inside the reactor. Reactors were fed once a day.

2.2 Analytical methods

Biowaste commodity class was analyzed in accordance with the procedure reported by MODECOM™ (1998). The reactor effluents were monitored 3 times per week in terms of TS, TVS, COD, TKN and P total. For TS determination, 105°C drying temperature was adopted and no losses were caused (Peces at al., 2014). The process stability parameters, namely pH, volatile fatty acid (VFA) content and distribution, conductivity, total and partial alkalinity and ammonia (NH_4^+–N), were checked daily. All the analyses performed according to the Standard Methods for Water and Wastewater Analysis (1998). The analysis of the volatile fatty acids was carried out with a Carlo Erba™ gas chromatograph equipped with a flame ionization detector (T = 200 °C), a fused silica capillary column Supelco NUKOL™ (15 m x 0.53 mm x 0.5 µm thickness of the film), while hydrogen was used as carrier gas. The analysis was conducted using a temperature ramp from 80 °C to 200 °C (10 °C / min). The samples were analyzed before being centrifuged and filtered with a 0.45 µm filter. Biogas production was monitored by a flow meter (Ritter Company™), while methane, carbon dioxide and oxygen in biogas were determined through a portable infrared gas analyzer GA2000™ (Geotechnical Instruments™) continuously and a Gas Cromatograph 6890N, Agilent Technology™, once a day.

The content of heavy metals and pathogens of fed substrate and digestates, in the two experimentations (mesophilic and thermophilic), were analyzed (EPA 3051A 2007 + EPA 6020A 2007).

3. Results and discussion

3.1 Biowaste pretreatment and composition

The biowaste collected in Treviso area and used in this experimentation showed the composition reported in table 1: fruit and vegetable waste were typically half of the waste material, a result in line with previous studies on this topic (see Valorgas D2.1 http://www.valorgas.soton.ac.uk/deliverables.htm) while pasta/bread and meat/seafood represented another 25% of the wasted food. Some 10% of the material was un-classified (melt material).

Table 1. Components of biowaste

Composition	Fresh matter, %	Dry matter, %
Fruits & Vegetables	46-58	42-52
Other kitchen waste *	16-25	15-22
Paper & cardboard	9-14	7-12
Not classifiable	8-14	6-12

* Putrescible material non-vegetable (eg pasta, cakes, meat, etc..). WW = wet weight. DW = dry weight

Biowaste compositional analysis (of five samples) showed that food waste was more than 82% of the total (on wet weight) while the remaining parts were paper (11%) and inert materials (7%) like glass and metals or textiles. The different fractions for each type of material in terms of wet and dry weight, and volatile fraction are presented in Table 2.

Table 2. Commodity characteristics of biowaste

Fractions	Wet weight	Dry matter	Volatile dry matter
	%	%	%
paper	10.75	11.25	12.87
plastic	0.85	1.20	1.31
inert	6.88	11.33	8.16
food waste	81.52	76.22	77.66

Table 3. Characteristics of biowaste, and pressed liquid and solid fractions

Substrate	TS g/kg biowaste	TVS g/kg biowaste	TVS/TS %	COD g/kg TS	rbCOD g/kg TS	TKN g/kg TS	P g/kg TS
biowaste	298.2±44.2	267.6±32.5	89.8±3	1,090±449	-	27±4	4.0±0.2
Liquid $_{bw}$	186.4±49.3	169.6±24.0	91±2	1,440±357	345±85	24±4	4.2±0.3
Solid $_{bw}$	378.2±34.3	343.4±18.9	89.6±1	1,389±498	-	23±6	3.9±0.4

As for the general chemico-physical characteristics, biowaste showed an average dry matter content of 298 gTS/kg, 90% volatile solids. The COD values were typically greater than 1090 gCOD/kg with a low nitrogen content.

The liquid phase obtained was particularly suitable for AD because of its total and volatile solids (91% of dry matter on average) very high COD content, and COD/N ratio.

3.2 Performance of the pilot scale reactors

The start-up phase of both mesophilic and thermophilic reactors was characterized by a gradual increase of the organic loading rate (OLR) starting from 1 kgVS/m^3_rd onwards with a fixed hydraulic retention time of 20 days; when a steady state condition was achieved the OLR applied was ranging between 3.0 and 3.5 kgTVS/m^3_rd.

In order to verify the process resilience also transient conditions were tested: transient conditions were obtained testing the system at different organic loading rates. In particular, the OLR was tripled (from 2 to 6 kgVS/ m^3_rd) on alternate days and stopping the feed once a week. Every day pH, ammonia, alkalinity (partial and total) and VFAs in the effluent as well as biogas production and its composition were analyzed before addition of fresh substrate.

Table 1. Time division of the trial and organic loads applied

	RUN I – Start up	**RUN II – SSC**	**RUN III – Transient**
OLR (kgVS/m^3_rd) Average Value (M)	1-2	3.5	3 – 6
RUNs time (d) MESOPHILIC	40	40	60 started from (110day)
OLR (kgVS/m^3_rd) Average Value (T)	1	3.5	3 – 6
RUNs time (d) THERMOPHILIC	80	40	60
HRTs Meso and Thermo	20 d	20 d	18/20 d

Reported values show how the two systems needed different time in order to conclude the start up phase and reach a steady state condition. The transient period was the same in both reactors, in order to make a good comparison of the results of the stressing tests.

3.2.1 Performances of the mesophilic anaerobic digestion process

The inoculum used for the mesophilic trials was anaerobically digested sludge originated from a full-scale anaerobic digestion process (Treviso Municipal Wastewater Treatment Plant). The pilot scale reactor was maintained at the operating temperature of 37°C with low loading rate (1 kgTVS/m^3_rd) for a week, in order to acclimatize the biomass to the liquid pressed organic stream. Initially the reactor was fed with an OLR of 4,19 kgCOD m^{-3} d^{-1}.
Once the methanogenic biomass was active and responding appropriately in terms of biogas quality, the reactor was fed daily, and the OLR was increased stepwise from 1 kgTVS/m^3_rd to 3.5 kgTVS/m^3_rd in 2 HRTs (RUN I, start up, from day 1 to day 40).
In steady state conditions the pH of the mesophilic AD was in the range 7.1 - 7.7 favoring the metabolic activities of fermentative bacteria and the growth of methanogens. The pH drop observed during start up period (days 1-7) was related to the high VFA concentration due to the sharp increase of acetate and propionate acids. However, the overall anaerobic process and methane production is not inhibited presumably because of the balanced presence of both acids (Zhang et al., 2014). After day 7 VFA concentration decreased indicating the adaptation of biomass to the new environmental conditions which signals the initiation of steady state phase (Gallert and Winter, 2005) during which VFA concentration acquires an average value of 912 mgVFA/l (predominantly acetic acid). The system didn't show any upset to its stability, thus indicating good robustness of the process also in transient conditions, a relevant aspect for the full-scale implementation of the process. As for pH, this remained constant, particularly in steady state conditions, with an average value around 7.7 because of the high buffer capacity of the system: this is highlighted by an average total alkalinity value of 5,177 mg$CaCO_3$/l (figure 1). The ratio between VFA concentration and alkalinity was also evaluated. Soluble COD (sCOD) showed an average value of 2,294 mgCOD/l. In steady state conditions the concentrations of the partial alkalinity

ranged between 2000 to 4500 mgCaCO_3/l (determined at pH 5.75), while the total alkalinity was greater and in the range 4500 to 6000 mgCaCO_3/l (determined at pH 4). These figures ensured sufficient buffer capacity: the ratio of VFA to total alkalinity (i.e. the difference between total and partial alkalinity compared to total alkalinity) was constantly below 0.3 indicating the stability of the AD processes in terms of volatile fatty acid accumulation (Ripley et al., 1986). The concentration of volatile fatty acids and alkalinity are the two parameters that show a more rapid variation when the system tends to be upset (Ahring et al. 1995, Bolzonella et al, 2003) since in case of organic overload, the concentration of fatty acids increases while the alkalinity tends to decrease. The relationship between these two parameters (Cecchi et al., 2005) is a useful stability indicator to be considered: ratio values around 0.3 indicate a stable operation of the AD process, while greater values may indicate the inception of instability. During organic loading increase the ratio was around 0.22, thus the system achieved a perfect steady state even with the transient increasing of the organic loading rate.

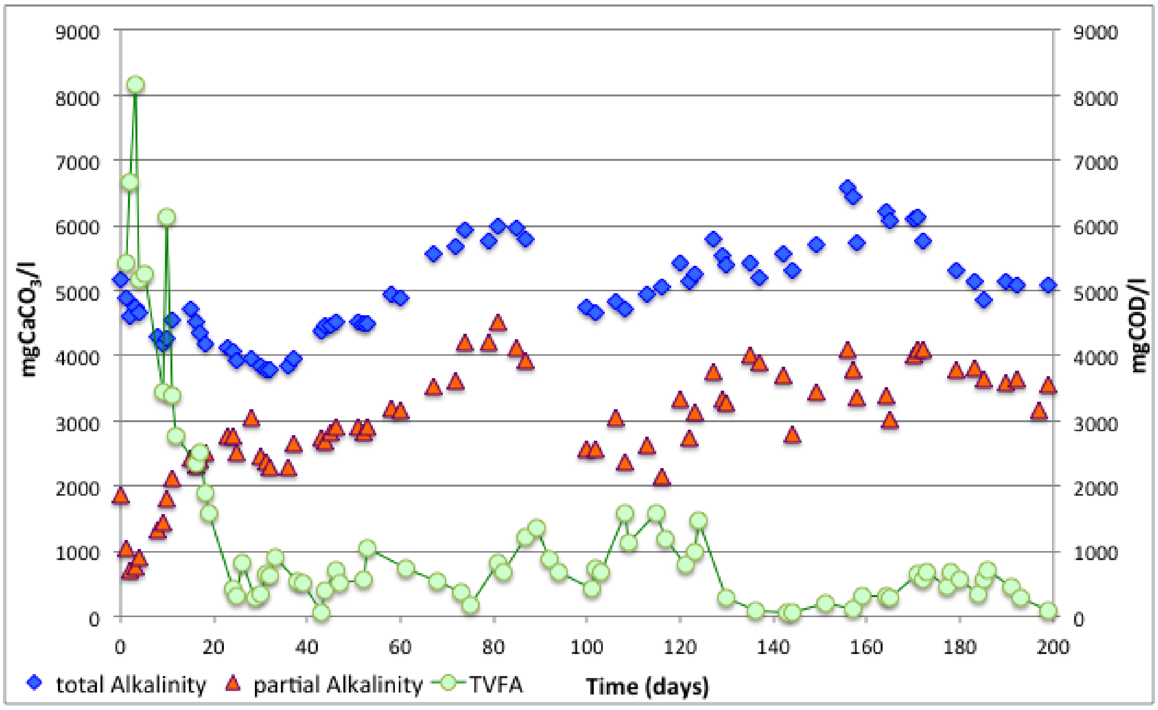


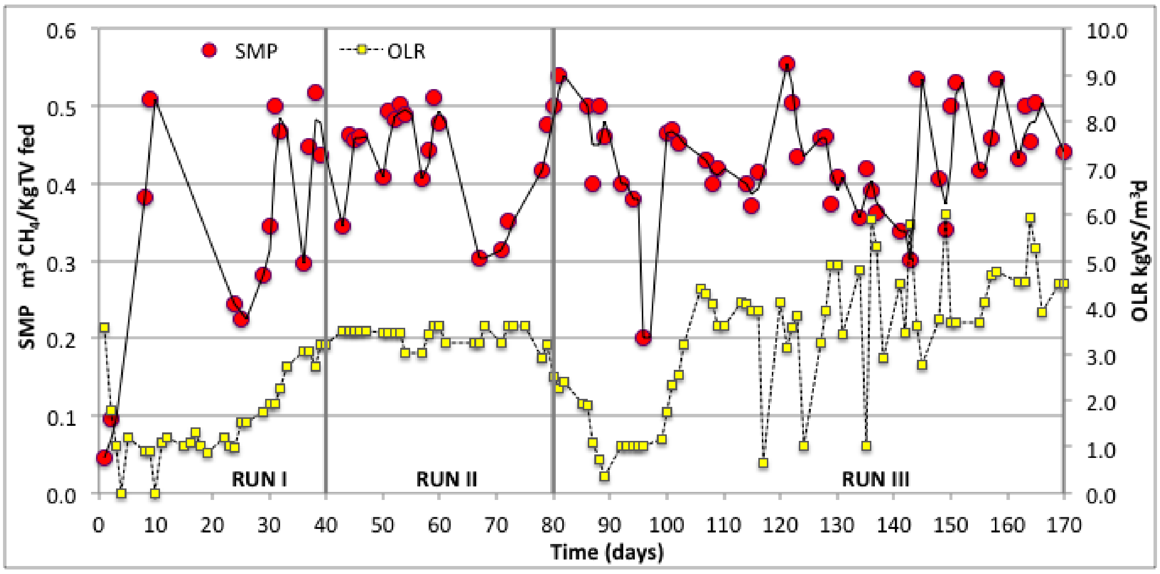
Figure 1. Alkalinity and VFAs trend during the mesophilic trial.

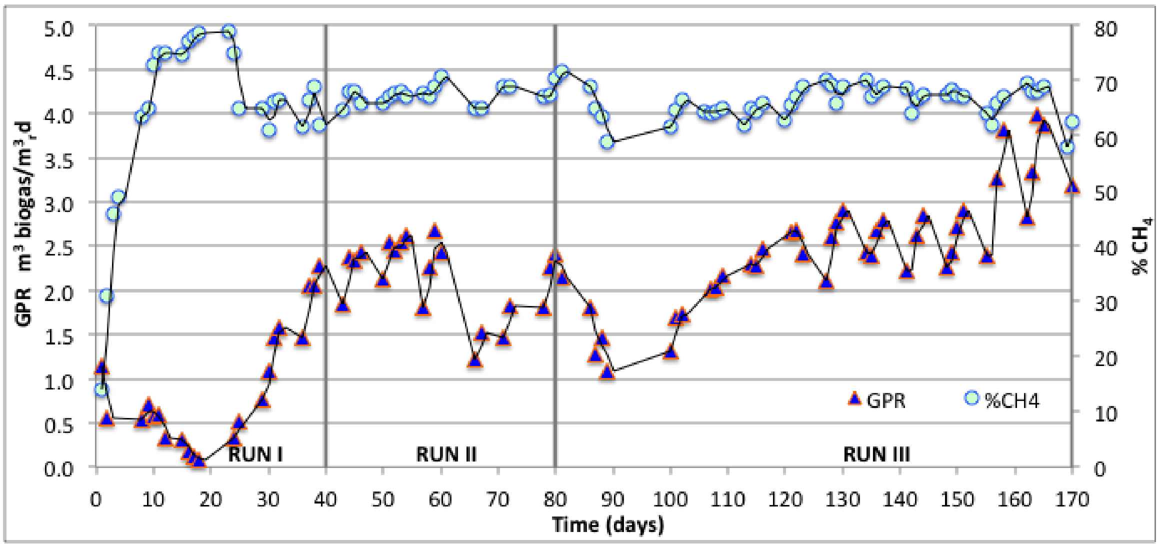
The use of a real substrate and the heterogeneity of biowaste, determined inevitable variations in the solid content in the reactor: the observed standard deviation was ± 39.3 gTS/kg).

The monitoring of the total ammonia showed an average value of 878 mgN-NH_4^+/l (St.Dev. ± 79), 64 mgN-NH_3/l free ammonia, well below the typical critical level for inhibition (Chen et al., 2008). The average content of total solids in the reactor remained almost constant with an average value of 22.5 gTS/kg (St.Dev. ± 1.9) and an average volatile solids content of 16.1 gTVS/kg (St.Dev. ± 0.7). The ratio between total solids and volatile shows an average value of 71.5% (TVS/TS), it is thus highlighted the capability of the system of converting the organic matter into biogas, leaving a residual dry matter content lower than 3% in digestate.

The biogas composition in terms of average percentage of methane detected in steady state condition (SSC) was 66% CH_4 and the remaining part CO_2. The average specific gas production (SGP) was found equal to 0.79 m^3biogas/kgTVS and the average specific methane production (SMP) was 0.47 m^3CH_4/kgTVS, while the average gas production rate (GPR) was 2.3 m^3biogas/m^3_rd. Profiles of specific methane production (SMP) during the experimental trials are shown in figure 2.

Figure 2. Specific methane production and OLR variations in mesophilic anaerobic digestion and methane percentage compared to the Gas Production Rate





Overall the mesophilic digestion process of the semi-liquid fraction of biowaste in steady state conditions showed great strength and resilience with reference to the process parameters (pH, alkalinity and VFA concentration, and biogas composition). Based on the aforementioned figures for each ton of biowaste semi liquid fraction, the biogas and methane production in AD mesophilic conditions equals to 148 and 98 m^3 respectively and corresponding to an expected power generation of around 300 kWh electrical energy (assuming biogas LHV=6.6 kWh/m^3biogas and 30 % energy conversion efficiency). A maximum value of 0.82 m^3biogas/kgTVS in terms of SGP was observed at an OLR of 4.5 kgTVS/m^3_rd. Interesting values in the velocity of biogas production were achieved in the latter period, with an average value of 3.1 m^3biogas/m^3_rd.

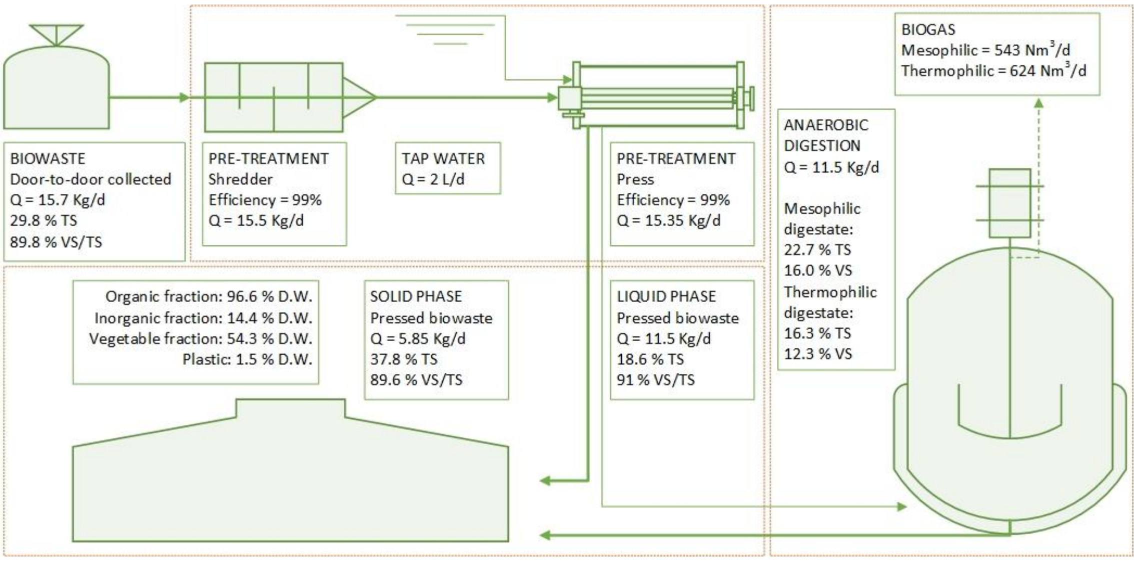
With specific reference to the mass balance of the AD system the average VS content of the influent was 790 gVS(in)/d, and the VS content of the output materials, namely biogas and digestate accounted for 512 and 259 gTS/d respectively. According to the above mentioned figures the mass balance accounts to 93%, with a 11.8% error, while the VS reduction was approximately 65%. Also the resulting digestate contains less than 3% residue expressed as dry matter.

Similar results were found for dry matter and COD thus confirming the quality of the calculation. The COD balance showed a deficit of 9.8%.

Also the mass balances for nutrients (nitrogen and phosphorus) were good: nitrogen balance reached 89.5% with an error (deficit) of 11.5% while the ammonification degree of the mesophilic system was 56.2%.

Phosphorus was slightly higher in the digester output with a balance of 105% and an excess of 5%. Process scheme with material flow characterization is showed in figure 3.

Figure 3. Process scheme including the material flow characterization.

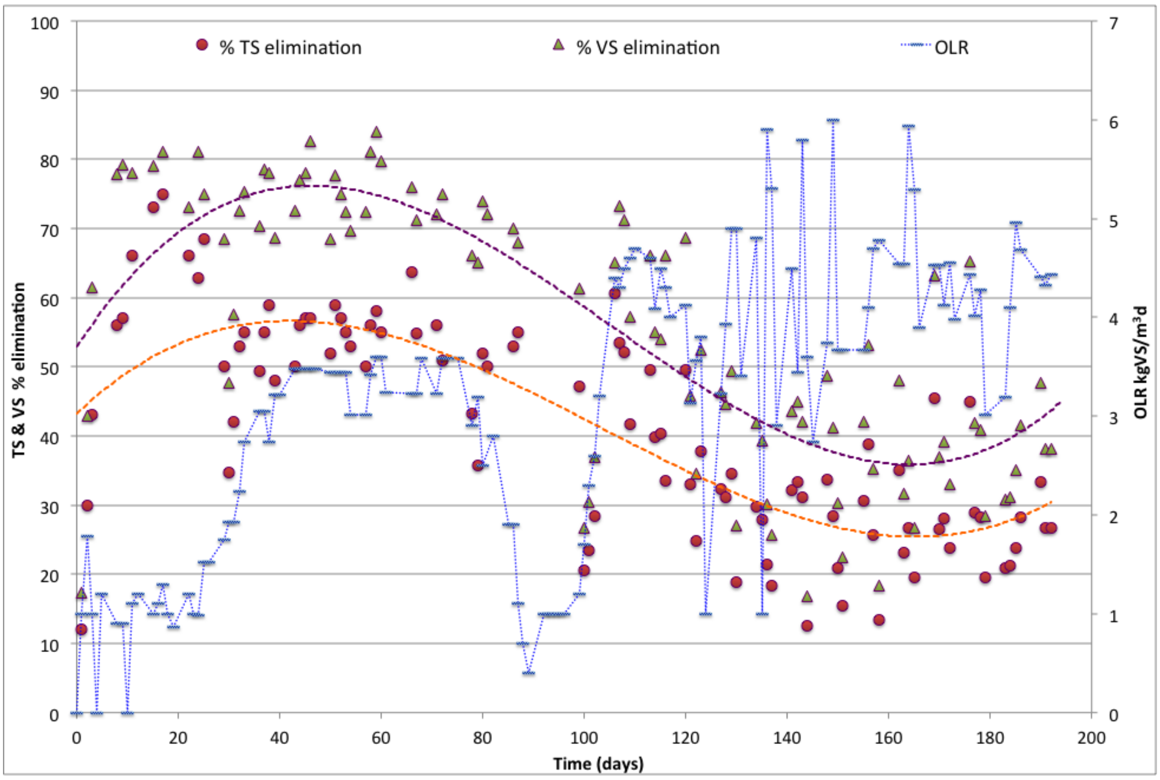


The removal efficiency of organic compounds was measured daily by determining the elimination of COD and Volatile Solids (VS) (Nayono et al., 2009). When SSC was reached, based on low residual fatty acids, stable biogas production, stable values for pH and COD elimination, TS and VS of the mesophilic system were also measured. In the first 22 days of operation the system reached a COD elimination more than 78% and then around 74% during SSC.

In the figure 4 the relationship between solids elimination, total solids and volatile solids compared to OLR trend are presented.

Compared to previous results of Nayono et al., (2009) we can underline that during SSC with an OLR of 3.5 kgVS/m^{3}d the mesophilic reactor showed a high efficiency on VS removal and during transient conditions, raising the OLR from 4.5 to 6 kgVS/m^{3}d the anaerobic process appeared to be less efficient. This is due to the stress condition the reactor had to endure, even if a VS elimination of 50% is considered close to the optimum for anaerobic degradation of press water (Nayono et al., 2009).

Figure 4. Total solids and volatile solids elimination during all the trial in mesophilic conditions.



3.2.2 Performances of the thermophilic anaerobic digestion process

The inoculum used for the thermophilic reactor was the same of used for the mesophilic tests. After the first days of operation in mesophilic conditions the working temperature was increased from 37°C to 55°C using the single-step strategy (Cecchi et al., 1993) and without feeding. The thermophilic conditions were reached in a couple of days and maintained for about ten days without feeding. In order to acclimate the biomass to the organic material, the reactor was started up with a low organic loading rate (1 kgTVS/m^3_rd) for one week, then the OLR was increased to 3.5 kgTVS/m^3_rd and maintained for about 2 HRTs (RUN I from day 0 to day 80, see figure 5).
The short chain volatile fatty acids concentration remained constantly below 1000 mg/l, with an average value of 489 mgVFA/l; acetate was the main compound found. Maintaining VFA at this level prevents potential process inhibition due to VFA accumulation which in turn leads to a decrease in pH and thereby declining concentration of free ammonia (NH_3). Average pH was around 8.1. The low pH fluctuations indicated the buffer capacity of the system which maintained pH at compatible levels with the methanogenic thermophilic levels.
Average total alkalinity (determined at pH 4) in steady-state conditions was 5,380 mg $CaCO_3$/l. Partial alkalinity (determined at pH 5.75) showed a profile in line with the trend of the volatile fatty acids, and consequently the difference between partial and total alkalinity, which is directly proportional to the concentration of VFA, remained constant. The values of total and partial alkalinity were 5,200 and 3,900 $CaCO_3$/l respectively, corresponding to a ratio value of 0.23 (VFA/alkalinity). Even in the thermophilic reactor the value of this ratio was stable, thus it justifies the possibility to increase the system to OLR of 4 - 4.5 kgTVS/m^3_rd, in fact. During the transient period (RUN III from day 120 to day 170) the best specific biogas productions were obtained

at OLR in the range 4 - 4.5 kgTVS/$m^3{}_r$d, with a SGP average value of 0.9 m^3biogas/kgTVS. Transient OLR conditions from 2 to 6 kgTVS/$m^3{}_r$d were evaluated. The VFA/alkalinity ratio of the transient OLR period had an average value of 0.27 as shown in Figure 4.

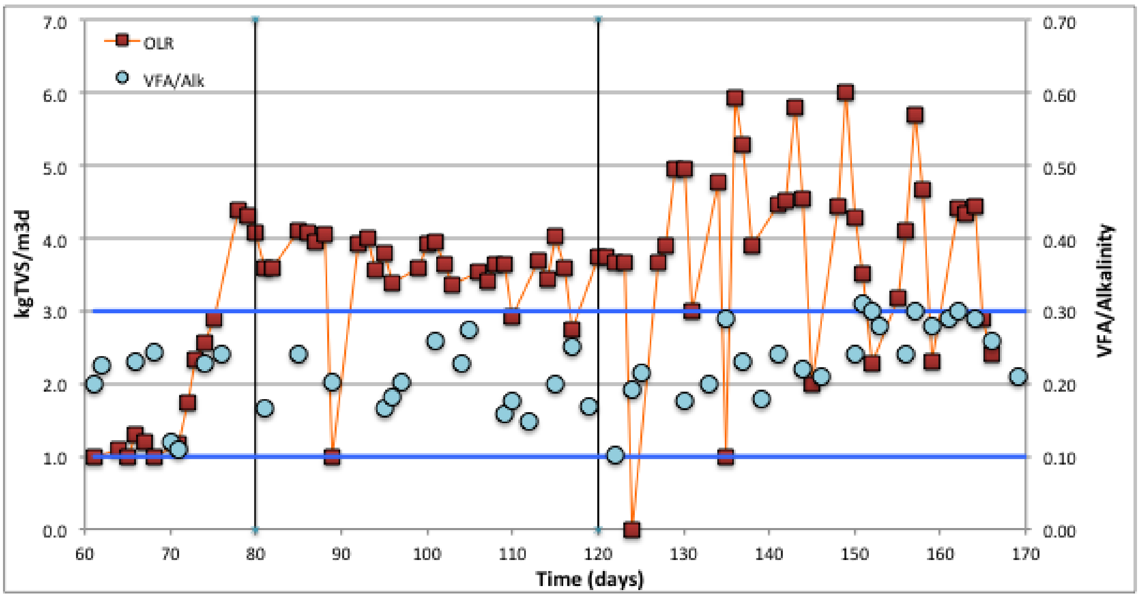


Figure 4. Trend of the thermophilic ratio volatile fatty acids and alkalinity with OLR variations

The average total ammonia concentration (as mgN-NH_4^+/l) was 1,004 mgN-NH_4^+/l, with maximum values of 1,086 mgN-NH_4^+/l. When OLR was increased to 4-4.5 kgVS/ $m^3{}_r$d, the corresponding value of free ammonia was 374 mgN - NH_3/l, a value below the inhibition limit, normally reported in literature (about 700 mgN/l, Angelidaki et al., 1994).

The content of total solids in the reactor remained almost constant with an average value of 16.3 gTS/kg and a volatile solids content of 12.3 gTVS/kg. The ratio between total and volatile solids shows an average value of 76.5% (TVS/TS), it's thus highlighted the large capacity of the system to convert the organic matter into biogas, leaving a residue of dry matter lower than 2% in digestate.

The average composition of the biogas in terms of methane percentage was high, equal to 68.8%, and the specific methane production (SMP) was 0.55 m^3CH_4/kgTVS (Figure 5). With regard to biogas and energy yield, the average specific gas and methane production equals to 0.90 m^3biogas/kgTVS and 0.55 m^3CH_4/kgTVS respectively, while the average gas production rate was 3.0 m^3biogas/m^3_rd. Based on the above figures for each tonne of biowaste semi liquid fraction, the biogas and methane production in AD thermophilic conditions equals approximately 166 and 113 m^3 respectively, corresponding to around 350 kWh electrical energy (assuming biogas LHV=6.9kWh/m^3 biogas and 30% energy conversion efficiency). Overall the thermophilic digestion process of biowaste semi-liquid fraction in steady state condition showed increased buffer capacity and higher biogas production potential compared to mesophilic digestion.

SGP reached a value as high as 0.94 m^3biogas/kgTVS at an OLR 4.5 kg TVS/m^3_rd transient period (RUN III, duration 4 HRTs), reporting an average increased value in biogas production of 0.9 m^3biogas/$kgTVS_{fed}$.

These values indicated the capability of the system of converting most of the organic material into biogas and are of particular significance.

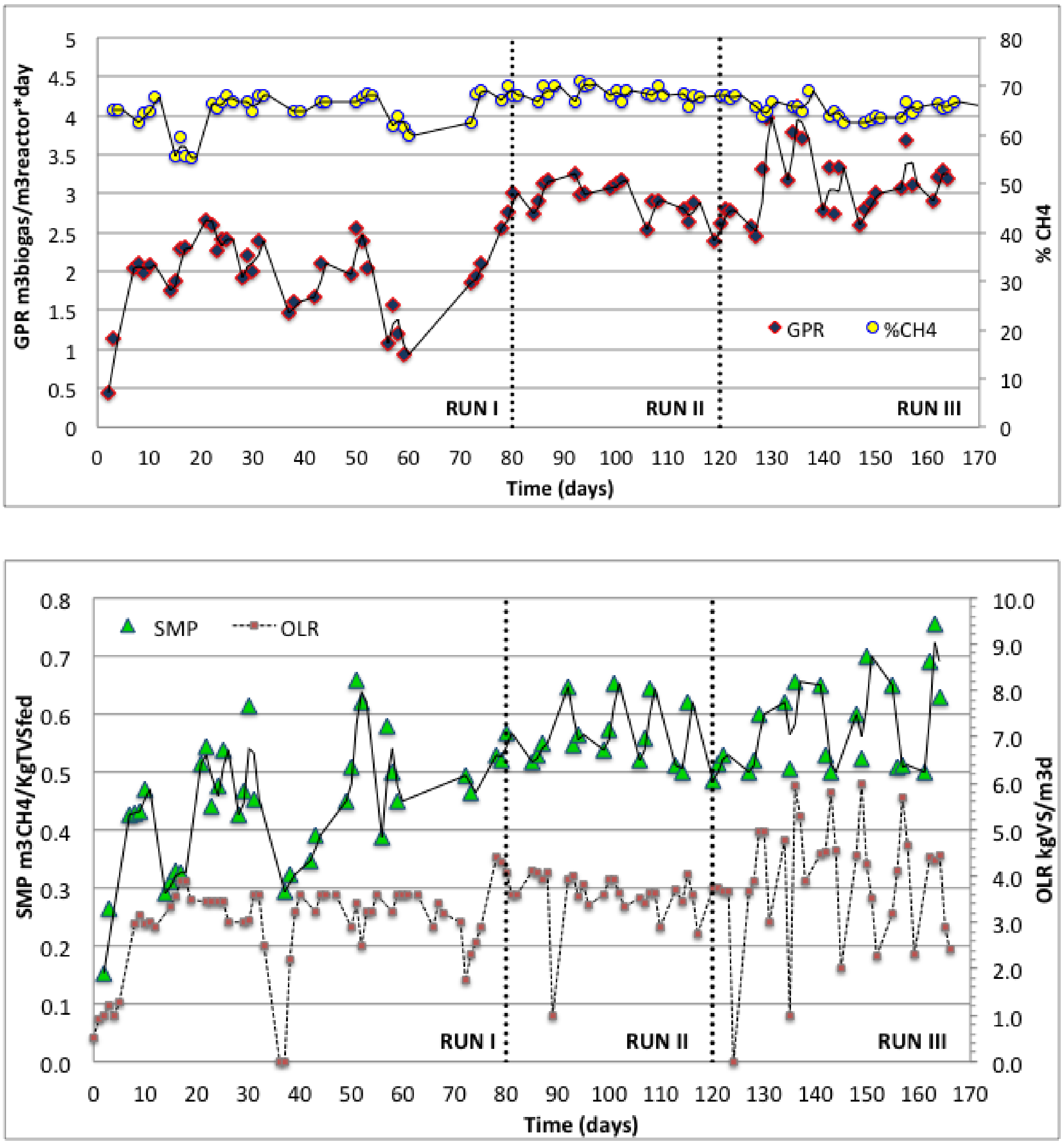


Figure 5. Specific methane production and OLR variations in thermophilic anaerobic digestion and methane percentage compared to the Gas Production Rate

During the steady state condition of the thermophilic reactor (RUN II from day 80 to day 120), with OLR between 3 and 3.5 kgTVS/$m^3{}_r$d, the mass balance around the system was calculated: the influent and effluent (as both digestate and biogas) quantity of volatile solids accounted for 790, 141 and 578 g/d, respectively. The balance was therefore 91%, with a 9% error. Similar results were found for dry matter and COD (errors of 11% and 11.5%, respectively) thus confirming the accuracy of the monitoring analysis data. The COD appeared to be in deficit-error of 11.4%.
Also the mass balances for nutrients (nitrogen and phosphorus) closed properly.
Nitrogen balance was 89.5% with a deficit of 10.5%. It is interesting to note here that ammonification degree was 60.2% in thermophilic conditions.
Phosphorus balance was 104% with a surplus of 4%.
In conclusion we can highlight that the mass balances of the thermophilic anaerobic system showed deficits or surpluses in matter transformation all within the margin of error in order to consider the system trial to be admissible from scientific opinion.

3.3 Energetic considerations

The mesophilic process allowed for the assessing of an average biogas production of some 148 m^3 per ton of pressed biowaste (99 m^3 of methane).
The thermophilic anaerobic digestion experimentation allowed for the assessing of an average production of some 166 m^3 biogas per ton of pressed biowaste (115 m^3 of methane), 11% more than mesophilic production.
The thermophilic anaerobic production used in a unit for the co-generation of heat and power this will give some 350 kWh of electric energy: the energy recovered from 1 ton of treated biowaste is therefore some 270 kWh.
On the other hand, an advanced industrial press machine for the treatment of biowaste is characterized by an installed power in the range 375-400 kW for a treatment capacity of

some 12 ton/h. The typical energy consumption is therefore some 33 $kWh_{consumed}$ per ton of treated biowaste.

The energy returned on energy invested (EROEI) per ton of biowaste treated is therefore very favorable and around 9 $kWh_{produced}/kWh_{consumed}$.

Clearly, this figure drastically reduces when considering the energy used for the whole treatment train (preparation treatments, pumping, composting, treatment of the liquid fraction of digestate and of the off-gas streams).

It is clear therefore how this kind of pressing pretreatment system permanently changes the paradigm of pre-treatment plants configuration: in fact two streams, one liquid and the other solid, of good quality are obtained with a low energy input.

3.4 Digestate characteristics

Heavy metals concentrations of biowaste and mesophilic and thermophilic digestate were checked five times during steady state conditions. The average concentrations of heavy metals in both the input matrix (biowaste) and in mesophilic/thermophilic digestates, were much lower than the limits of the technical proposals End-of-Waste criteria (EoW-2014) elaborated by the Joint Research Center of Sevilla, as showed in table 5. Concentrations referred to dry matter were typically greater in digestate because of the high conversion capability of the anaerobic process.

Table 5. Heavy metals concentrations (mesophilic and thermophilic conditions)

	EoW 2014	BIOWASTE	MESOPHILIC DIGESTATE	THERMOPHILIC DIGESTATE
Cu mg/kg d.m.	200	47±5	68.1±3.2	52.5±4.1
Zn mg/kg d.m.	600	112±28	155±13	129±17

Pb mg/kg d.m.	120	1.54±0.8	17.3±2.4	7.81±1.3
Ni mg/kg d.m.	50	43.7±3	42.1±1.6	27±0.5
Cr tot mg/kg d.m.	100	61.5±9	85.9±4.1	51.5±2.3
Cd mg/kg d.m.	1.5	0.4±0.2	0.23±0.14	0.26±0.08
Hg mg/kg d.m.	1	0.055±0.005	0.24±0.09	0.08±0.02
As mg/kg d.m.	10	0.24±0.1	0.25±0.09	0.19±0.03

Biowaste is known to contain pathogenic bacteria such as Salmonella and other microorganisms that may be a health risk for both people and animals (Sahlström 2003). The content of pathogens of fed substrate and both effluents digestates, in the two experimentations, was analyzed through five replicates. While Salmonella spp was never found, the limit of 1000 CFU/g for E.coli proposed in the End of Waste Criteria technical report (2014) was reached only occasionally (Table 6). This suggests the opportunity to treat digestate in a post-composting process in order to reduce the presence of enteric bacteria (Cekmecelioglu et al., 2005). Several experimental investigations demonstrated that rapid inactivation of Escherichia coli and Salmonella spp. occurs by thermophilic digestion (Smith at al., 2005, Wagner et al., 2008).

As for fertilizing properties, AD allowed getting a final product (digestate) with very good fertilizing properties because of the high nutrient content (C, N, P, K) in available forms (Tambone et al., 2010).

Table 6. Pathogens analysis

SAMPLE	TBC 37°C ISS 004A	TBC 22°C ISS 004A	*E.coli*	total Coliform	*Salmonella spp* ISS 011A
Biowaste	$4 \cdot 10^8$ UFC/g	$8 \cdot 10^8$ UFC/g	$7 \cdot 10^5$ UFC/g	$6 \cdot 10^5$ UFC/g	absent
Thermophilic digestate	$1 \cdot 10^7$ UFC/g	$1 \cdot 10^7$ UFC/g	$4 \cdot 10^3$ UFC/g	$1 \cdot 10^3$ UFC/g	absent
Mesophilic digestate	$3 \cdot 10^6$ UFC/g	$4 \cdot 10^6$ UFC/g	$3 \cdot 10^3$ UFC/g	$2 \cdot 10^4$ UFC/g	absent

4. Conclusions

The liquid fraction of pressed biowaste was treated through anaerobic digestion. The solid fraction should be used for composting with the dewatered digestate and some bulking material. Adopting this technique the EROEI for ton of biowaste treated is positive and at least around 8.9 $kWh_{produced}$ / $kWh_{consumed}$.
Mesophilic digestion gave an average biogas production of 0.79 m^3biogas /kgTVS with 66.0% methane content that has the potential to deliver approximately 300kWh_e per tonne of semi-liquid biowaste, while in the case of thermophilic conditions the average biogas production is 0.90 m^3biogas/kgTVS with 68.8% methane content producing theoretically about 350kWh_e per tonne of semi-liquid biowaste treated.
The application of press systems for the separation of segregated biowaste into semi-liquid and semi-solid fraction can be beneficial for further optimizing biowaste treatment in integrated anaerobic- aerobic systems. Steady states conditions in the AD process were maintained even when subjected to transient OLR conditions from 3 to 6 kgTVS/m^3_rd.

Heavy metals concentrations and pathogens were below the limits reported by “End-of-Waste” criteria (2014) for future legislative developments, thus indicating the good digestate quality and its possible use for agronomic purposes.

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7. Figure Captions

Figure 1. Alkalinity and VFAs trend during the mesophilic trial.

Figure 2. Specific methane production and OLR variations in mesophilic anaerobic digestion and methane percentage compared to the Gas Production Rate.

Figure 3. Process scheme including the material flow characterization.

Figure 4. Total solids and volatile solids elimination during all the trial in mesophilic conditions.

Figure 5. Trend of the thermophilic ratio volatile fatty acids and alkalinity with OLR variations.

Figure 6. Specific methane production and OLR variations in thermophilic anaerobic digestion and methane percentage compared to the Gas Production Rate.

Highlights:

- Truly new and advanced low energy demand pre-treatment process of biowaste
- Anaerobic digestion of highly biodegradable liquid biowaste from kerbside collection
- Transient meso-thermophilic conditions by organic loading rate perturbations tested
- Heavy metals and pathogens of fed substrate and effluent digestates were analyzed
- High biogas yields, good quality of digestates, possible use for agronomic purposes