Single-phase anaerobic digestion of the organic fraction of municipal solid waste without dilution: reactor stability and process performance for small size and decentralized plants

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Abstract

The Anaerobic Digestion (AD) of the Organic Fraction of Municipal Solid Waste (OFMSW) is a technology studied since many years and a lot of literature is available about this process. Research has usually been direct on how to improve process control efficiency, but this approach has historically favoured the development of centralized plants where the OFMSW is generally co-digested with waste activated sludge in Wet digester or with lignocellulosic wastes in Dry fermenters. Centralized plants imply however some environmental impacts that prevent a real massive diffusion of the AD treatment technology. At the threshold of 2020, we are still digesting less than 5% of the organic wastes both in Europe and in the USA, with the sad consequence of losing the benefit of the potential renewable energy production. Pursuing the criteria of maximizing the balance between profit and impacts, an innovative lay-out is proposed with the ultimate target of stimulating a capillary diffusion of decentralized, small size, AD plants.

This research demonstrates that the Source Separated SS-OFMSW can be treated in a mesophilic plug flow fermenter applying high OLR (6.2 kgVS/m^{3}d), without dilution and without any co-substrates. A proper and efficient mixing system is essential to control the process. The process results stable as single stage reactor and with no digestate recirculation, obtaining a specific gas production (SGP) of 0.67 m^3/kgVS in terms of biogas, and of 0.41 m^3/kgVSd in terms of methane. High reactor volume exploitation and smaller plants construction are feasible, reaching a Gas Production Rate (GPR) of 4.5 m^3/m^{3}d.

1. Introduction

The Waste Framework Directive introduced in Europe to support the Organic Fraction of Municipal Solid Waste (OFMSW) treatment for energy recovery, has encouraged a widespread diffusion of Anaerobic Digestion (AD) plants in EU countries (EU directive 2008/98/EC). Literature on the OFMSW treatment capacity and number of installed AD plants in Europe is not so updated, and a lack of updated data is also reported in other papers [1]. The last review paper is by L. De Baere and B. Mattheeuws (2012), in which authors reported 244 AD plants for almost 8 million overall ton of OFMSW treated in 17 EU countries [2]. Even if less specific, more updated data are reported by the European Biogas Association (EBA); they refers of an overall 17,662 existing plants in 2016, with a +283% increasing since the 2009 [3]. Most of them are fed with agricultural residuals: with 12,496 installations, agro-wastes plants cover the 70% of the total AD installed units. Considering the food waste treatment capacity, a total of 688 AD installations fed with generic bio-waste residuals (municipal waste, household waste and industrial waste) are reported by EBA for 2016 [3]. The success of AD technology is its capability to offer a double profit from waste treatment and green energy production. Being AD such a well-established and widespread technology, much attention is given today to its environmental impacts with particular attentions to water consumption and soil consumption. Large and centralized plants are getting always more unpopular, because, in addition to the impacts mentioned above, they also implies transfer of waste from high distances with negative repercussion on traffic and air pollution as well as costs for substrate transportation and digester construction [4]. As OFMSW is by itself a dispersed source of feedstock, the risk of supporting the centralized AD plant diffusion is of losing the environmental benefit of the technique [5]. In order to favor the transition from an economy of scale to an economy of numbers in the waste management sector [5], it must be noted that the type of full scale processes adopted today for OFMSW treatment, have often very limiting disadvantages due to their collateral environmental impacts, so they are not suitable for a capillary widespread diffusion of small scale OFMSW treatment plants. The objective of this study is to investigate the possibility to set up an innovative lay-out able to encourage the diffusion of small AD plants, easy to operate with OFMSW, and with low environmental impact. Having an easier and more attractive technology would probably help to increase the percentage of OFMSW currently digested, as only the 5% of the food waste is to date sent to the AD in Europe [1], and only the 2% in the USA [4].

A brief analysis of the typical conditions applied at the full scale AD plants today are reported below, with the objective to identify the benefit of every single process condition, and why they cannot support a real and capillary proliferation of small size AD plants. A different layout is then proposed, putting together the best operative conditions to create an efficient and sustainable small AD plants network. An experimental study is then set up at pilot scale to understand if a combined layout can assure a sustainable process under the biochemical point of view.

If Anaerobic Digestion must be applied to OFMSW as energy recovery treatment, the choice of process technology is done considering three aspects: the Total Solids (TS) content, the types of co-substrates to be added, and the process configuration (single-phase versus two-phase) [6].

Considering the TS, the distinction is generally done between Wet process (or Low-Solids, LS) and Dry process (or High-Solids, HS) in which the TS content is below 10% and above 15% respectively [6]. Wet or LS digesters are the firsts type of reactors developed since the 1930 by A. M. Buswell for wastewater treatment, at the time when firsts attempts on AD were being made on liquid wastes, and when the organic solid wastes were still not considered for AD treatment [7]. As it is the most developed technology, wet digesters have the advantages to be supported by the oldest experience in plant design. Another advantage of Wet digestion is the easiness of process control due to generally low OLR and to toxic dilution. On the other side, Dry processes such as Valorga, Dranco, Kompogas or Linde (TS>15%) [8], have the main advantage to allow the reduction of reactor volume [9]. Disadvantages of Wet digesters are mainly related to the need of an elevate dilution of the original food waste, because pumps and mixing system are suited for very liquid material. The elevate dilution could leads to key troubles: sedimentations in the reactor and in the pipeline, a large reactor volume to be built, and a very low TS content in the exhaust digestate, factor this one that determine a worse predisposition to aerobic stabilization and to its transformation in soil amendment for agriculture re-use [10] [11]. Dry digesters on the other hand have disadvantages mainly related to the reduced kinetics expected as a consequence of the hampered liquid/gas mass transfer, and the high risk of acidification for organic overloading [12]. As consequence, dry digestion has the significant limit of having a lower degradation efficiency and lower biogas production, compared to wet systems, as reported by many review papers [8] [13] [14] [15] [16]. Dry digestion hence, resulting in less renewable energy production than potential, means today a wasted opportunity both for environment and for profit, since renewable energy is usually economically supported by the current regulation in EU. The opportunity to use HS AD for small scale digesters have already been investigated by M. Fagbohungbe et al. (2015), concluding that the limited methane production is a limiting factor [8]. Working at intermediate conditions, with a TS content due to just OFMSW and avoiding extra solids addition, would probably results in a high Gas Production Rate (GPR), sign of a highly efficient exploitation of the reactor volume. This would be of interests when the target is to obtain small size plants.

Concerning the possible co-substrates, usually co-digestion is largely preferred than mono-digestion. At the full-scale, the most utilized co-materials are by far the green wastes and the sewage sludge. Principal advantages of co-digestion are linked to its capability to control inhibition and toxicity (ammonia and high OLR) as a way to dilute the OFMSW with other low toxic compounds [17][18] [19] [20]. Zhang et. al [21] reports that the 33% of literature on strategies for enhancing biogas production from solid organic wastes published during 2013–2017, is on improvement of the biological process with co-digestion; that demonstrates how much important co-digestion is today considered for AD. When a full-scale plant is operated, some negative implication of co-digestion are however to be faced, related in particular with the availability of the co-substrate, as already reported by M. Ortner [22]. Regarding using green waste as co-substrate, the main problem is related to its collection: where they are collected separately from food waste as in Italy or Scandinavia [23], they are probably not together available at the same treatment site. Moreover, the addition of a coarse lignocellulosic fraction to a substrate relatively easy to pump, makes the plant much more complex under the engineering point of view. Concerning the use of sewage sludge from wastewater treatment as co-substrate for OFMSW, it was deeply evaluated from a scientific point of view and the feasibility of the approach is justified as a solution for wastewater treatment with the recovery of a waste stream such as sludge. This approach however implies two main critical issues. Firstly, co-digestion of OFMSW and sludge would mean the upgrade of the existing wastewater treatment plants with a solid waste reception and treatment line, that is justified by a scientific point of view, but is often practically not easy due to financial issues and policy restrictions [17]. Secondly, the digestate from OFMSW and sludge could contain more heavy metals compared to the digestate from mono-digestion of OFMSW, making in this way more complex its reintroduction into agriculture, so that, in some cases, it is better to maintain the wastewater sludge and the OFMSW treatments in two different channels. Hence, despite co-digestion is a more largely applied condition, if the target is a spread of small and easy-to-operate AD plants for OFMSW, it would be encouraged by the adopting of mono-digestion to avoid the disadvantages above.

Considering the choose of single or two phases processes, most of the authors agree that the two-phase approach is the one with more benefits [24]. In AD, the growth of acidogenic and methanogenic microorganisms are characterized by different kinetics. Acidogenesis occurs faster than methanogenesis, and this implies a high solubilization rate of the organic waste once fed, resulting in a process balance often unstable [25]. Besides an increase in process stability, having two reactors in series also permits to recirculate digestate with fresh biomass from the second to the first phase, with a positive implication to the process control in the first reactor that operates at high OLR [26]. The possibility of adopting a system based on single-phase digestion would however clearly be less expensive and with small impact on soil consumption, and it would definitely make easier the diffusion of capillary AD digesters in the EU countries.

As mentioned above, the objective of this study is to investigate the possibility to operate an AD plant with a mix of conditions that result in an improved and innovative scenario for OFMSW treatment, with the ultimate target of encouraging capillary diffusion of decentralized, small size, AD plants. Other authors have already highlighted the benefit of OFMSW AD plants decentralization, both for environmental reasons [5] than for economic and social aspects [27]. The system identified to reach this target consists of a single-phase reactor, where mono-digestion of not diluted OFMSW is operated at mesophilic conditions. Food waste is fed as it comes out from pretreatment, at 21,5% of TS, to avoid any water consumption or additional increase in the exhaust digestate volume. A plug flow reactor (PFR) reactor is chosen to avoid sedimentation and to maximize the agitation efficiency. The stirring system consists of an agitator that runs the entire length of the fermenter, grazes the bottom of the digester, and continuously breaks the digestate surface to avoid also crusts formation. The other process conditions are reported in the next paragraphs and they are chosen on the basis of literature review and experience in full scale plant operating.

2. Materials and methods

2.1. Substrate characterization

The SS-OFMSW was collected at the composting plant of Castiglione delle Stiviere (Lombardy, Italy), that treats 32.000 t/y of household food waste from separate collection (kitchen residuals only), collected through compostable bio-waste bags. The food waste comes from a maximum of 40 km from the treating plant, where it is delivered daily. At the composting plant, the waste is initially pre-treated with a Screw Press by Cesaro Mac. Import (Italy) and modified for optimization by the owner. The pre-treated organic waste is hence mixed with green waste for aerobic composting. For the present study, the organic waste was taken just after pre-treatment, so it results clean from coarse inorganic impurities, but it has no lignocellulosic fraction added. According to the analytical monitoring made by the plant owner, inert impurities are lower than 5%. The OFMSW was collected once per week and maintained at -18°C until the use in the experimental test. Table 1 reports average characterization of the fed OFMSW. Total solids (TS) and volatile solids (VS) analysis was measured three times per week; pH, chemical oxygen demand (COD), Ammonia and Total Kijendhal Nitrogen (TKN) were analysed once per week.

Table 1: OFMSW physical-chemical characterization

	TS (g/kg)	VS (g/kg)	VS (%TS)	pH	Total COD (gO_2/kg)	$N\text{-}NH_4^+$ (g/l)	TKN (g/kgTS)
Mean Value	214.5	171.8	80.1%	5.3	203.5	0.63	4.7
Standard Deviation	±11.0	±10.6	±3.8	±0.3	±24.9	±0.10	±0.9
Number of samples	23	23	23	10	10	10	10

2.2. Pilot Plant set up

The experimental activity was carried out at pilot scale with a single-phase plug flow reactor (PFR). The pilot reactor was designed and built by MicrobEnergy, and it is a downscaled reproduction of the fermenter Euco®, built by Schmack Biogas at the industrial scale. The stainless-steel parallelepiped reactor is 0.375 m wide, 1.2 m long and 0.475 m high; it has a gross volume of 215 l. Working level is kept at 0.355 m for a net working volume of 160 l. The 55 l head volume is occupied by the biogas. The digester is mixed by a paddle stirrer that runs the entire digester length. It is equipped with blades that reach 1.2 cm from the bottom and reach up to 0.360m in height so that the formation of sediment and floating scabs are prevented. Figure 1 shows a detail of the agitation system.

Figure 1: Detail of the pilot scale reactor agitation system

The heating system is electric and consists of a heating mat at the bottom and a heating wire around the walls. A layer of 2 cm of expanded synthetic polyethylene assures thermal insulation. Temperature is monitored continuously by two temperature probes (PT100) and was maintained at 38°C. Two 2” ball valves permits to sample the digestate. The feeding systems consists of a 30 l tank where an oblique cochlea loads the OFMSW below the digestate level to prevent biogas from escaping. In Figure 2 is reported the calibration line according to which the food waste is loaded automatically based on the operating time of the cochlea and according to a OFMSW flow rate of 0.750 kg/min R^2 of the calibration line is 0.9738. Feeding occurs 10 times per day and 7/7d.

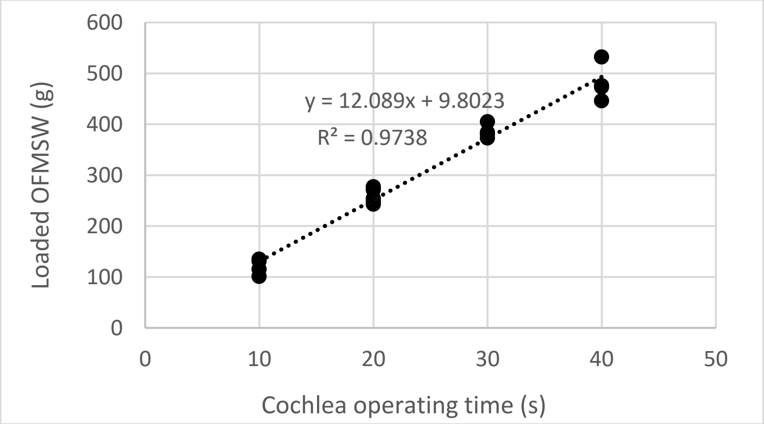

Figure 2: Calibration line of the automatic OFMSW loading system

A peristaltic pump and a pneumatic valve operate the automatic digestate discharge before every feed loading cycle. At the steady state, the digestate discharge was controlled by an Endress+Hauser PROMAG 5 flow meter, the discharge volume was set to be the 73% of the feeding volume according to empirical observation (with this value the digestate level in the fermenter was kept stable at 0.355 m). Before discharge, the digestate was collected to a graduated thank to control the right daily output volume. The gas was collected at the top of the fermenter at a pressure of 4.5 mbar and the gas production was measured by a Ritter gas Counter model TG1/5 with a pulse generator connected with a Programmable Logic Controller (PLC). Gas composition was monitored automatically and continuously every 6 hours with a ETG biogas analyser model MCA 100 Bio-P. All the plant components were connected to a PLC that permits fully automatic control of the process and automatic data recording. The pilot plant used a Siemens PLC programmed with S7 logic. The operator software was designed by Schmack Biogas and provided with remote control. Reactor stability parameters (TS, VS, volatile fatty acid (VFA), pH, Alkalinity, N-NH$_4^+$) was analysed two times per week.

2.3. Analytical Methods

On OFMSW, Total Solids (TS) and volatile solids (VS) analysis was measured two times per week; pH, Chemical Oxygen Demand (COD), Ammonia Nitrogen (N-NH4$^+$) and Total Nitrogen (TN) were analysed once per week. COD was measured both on the liquid fraction collected after centrifugation at 5.000 rpm as soluble COD (sCOD) and on the dried material. The COD on the two fractions were used to calculate the total COD per unit of fresh substrate. Similarly, nitrogen was measured on the liquid fraction after centrifugation at 5.000 rpm as N-NH$_4^+$, and in the dried material it was measured as Total Kjeldahl Nitrogen (TKN); the two fractions were then used to calculate the TN per unit of fresh material. On the digestate, stability parameters such as TS, VS, Volatile Fatty Acid (VFA), pH, Total and Partial Alkalinity (TA and PA) and N-NH$_4^+$ were analysed two times per week. All the analyses, except for VFA, were analysed according to the Standard Methods (APHA/AWWA/WEF, 1998). VFAs were analysed using a Gas Chromatograph (GC) (Carlo Erba instruments) with H_2 as gas carrier. The GC was equipped with a Fused Silica Capillary Column (Supelco Nukol TM, 15 m, 0.53 mm x 0.5 mm film thickness) and with a flame ionization detector (200°C). Temperature ramp started from 80°C to reach 200°C through two other steps at 140°C and 160°C, with a rate of 10°C/min. Samples were centrifuged and filtrated on a 0.22 mm membrane before the GC analysis. Butyric, Valeric and Hexanoic acids were each analysed in the iso- and n-stoichiometric forms, they were then reported as cumulative concentration.

2.4. Experimental Design

The reactor was filled up with an inoculum from a previous unpublished continuous test. It was conducted in the same pilot plant for three months for testing the process response to the OLR variation and plan the biological start-up of the present work. The same OFMSW was utilized and the same temperature was applied. After that test, the digestate was sieved at 1 mm and left mixing at 38°C for one month. Before starting with the test related to the present study, the inoculum was sampled and its physical-chemical characterization is reported in Table 2.

Table 2: physical-chemical characterization of the inoculum, from pilot scale previous unpublished tests

Parameter	Average Value	Standard Deviation
TS (%)	3.00	±0.10
VS (%)	1.40	±0.20
VS (%TS)	47.40	±7.90
pH	8.05	±0.065
Total Alkalinity (mgCaCO$_3$/l)	7,487	±353
Partial Alkalinity (mgCaCO$_3$/l)	9,815	±96
Total VFA (mgCOD/l)	2,004	±863
Acetic Acid (mgCOD/l)	1,180	±754
Propionic Acid (mgCOD/l)	680	±168
Butirric Acid (mgCOD/l)	42	±22
Pentanoic Acid (mgCOD/l)	46	±29
Hexanoic Acid (mgCOD/l)	19	±5
Eptanoic Acid (mgCOD/l)	0	±0
NH$_4^+$ (mg/l)	2.0	±0.1

The biological start-up was conducted applying a low initial loading rate, increased progressively to allow a gradual acclimation of the biomass according to Agelidaki et al [28]. The feeding strategy reported by Bolzonella et al. [29] and the authors experience with full scale start-up were also considered. Feeding began at day 1 with an OLR of 1.25 kgVS/m^{3}d. It was then increased by 1.25 kgVS/m^{3}d every 7 days. Once reached an OLR of 6 kgVS/m^{3}d, the OLR was stabilized and then raised up to final target OLR of 6.2 kgVS/m^{3}d after 16 days. The target OLR of 6.2 kgVS/m^{3}d was fixed on the basis of unpublished previous experiences of the same authors, results that showed unbalanced process conditions at an OLR between 6.5 and 7.0 kgVS/m^{3}d. Pavan et al. (2000) confirms that for highly biodegradable OFMSW, the OLR should not exceed 6 kgVS/m^{3}d [30]. According to Tyagi et al. (2010) [17] the OLR of 6.2 kgVS/m^{3}d can be considered an high loading rate, as in similar experiences the same parameter is mostly applied under 4 kgVS/m^{3}d. Stability parameters were analysed from the beginning to control the right microbial adaptation during the OLR increasing. Once reached the steady state, the test was kept running for a minimum of 3 HRT and/or full experimental evidence of stability.

3. Results and Discussion

3.1. Start up

As long as the OLR was increased, an increasing daily gas production was observed. Figure 3a shows the high correlation between the OLR and gas production during the start up. Target OLR of 6.2 kgVS/m^{3}d was reached after day 46 and a visible stability in gas production was reached after day 55, since the daily biogas production stabilized to an average of 719 l/day. As showed in Figure 3b, CH_4 and CO_2 concentration showed at the beginning a certain variability, in particular during the firsts 30 days of test when the OLR was increase from 1,25 kgVS/m^{3}d to 5 kgVS/m^{3}d. After day 30 a high degree of stability was observed for the gas quality, with a biogas characterized by 61,4% of CH_4 and 38,3% CO_2. Values shown in the graph are the daily average of the four gas analysis performed per day every 6 hours.

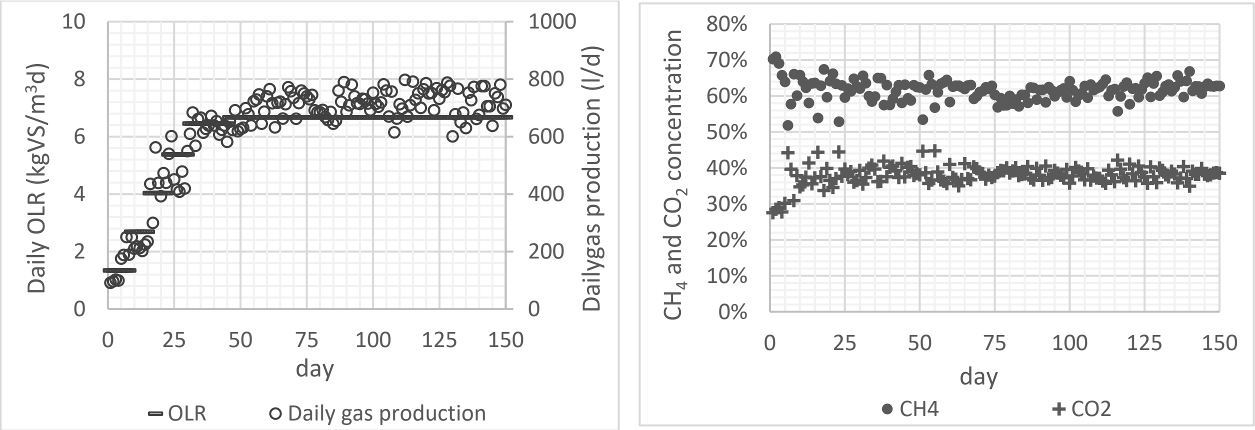

Figure 3: a) OLR and daily gas production observed during the test - b) Methane and Carbon dioxide monitored during the test

Figure 4a shows the pH and alkalinity trends, and their correlation. pH started at the value of 8.05 in the inoculum and showed since the beginning a reasonable stability, maintaining its variation between the range of 7.5 and 8.0. Alkalinity on the other hand needed some time to reach stabilization, and that happened after day 70. The difference between partial and total alkalinity has however been quite stable along all the test, with a minimum of 1,245 mgCaCO$_3$/l (day 11) and a maximum of 2,988 mgCaCO$_3$/l (day 123). Ammonia showed a certain variation and a positive trend for the firsts 50 days of the test, to then reach a quite high degree of stability. The highest value of ammonia was detected at day 15 at a concentration of 2.70 g/l. Figure 5b shows the variation of ammonia concentration during the test.

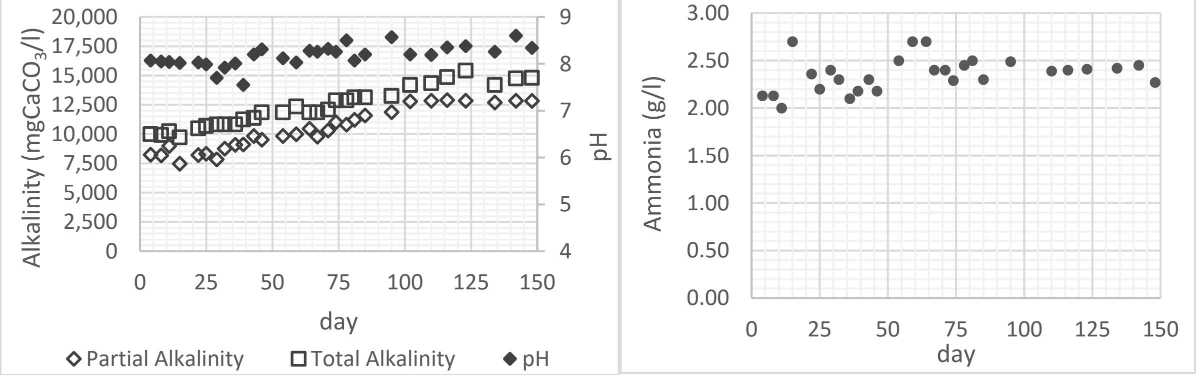

Figure 4: a) Alkalinity and pH monitored during the test – b) Ammonia concentration on the liquid phase

Regarding VFA it is not possible to identify a proper trend during the test. Results on Acetic acid and Propionic acid monitoring are reported respectively in Figure 5a and Figure 5b. It is possibile to identify two intermediate peaks for bot acetic and propionic acid as already noted in previous studies [31]. The first peak is visible around day 25, when the microorganism acclimatation was under stress due to the increasing of OLR from 3.75 kgVS/m^{3}d to 5.00 kgVS/m^{3}d. The second peak was observed at around day 70, few weeks later the stabilization of the target OLR of 6,2 kgVS/m^{3}d. After that, both acetic and propionic acid drop down under 1,000 mgCOD/l each

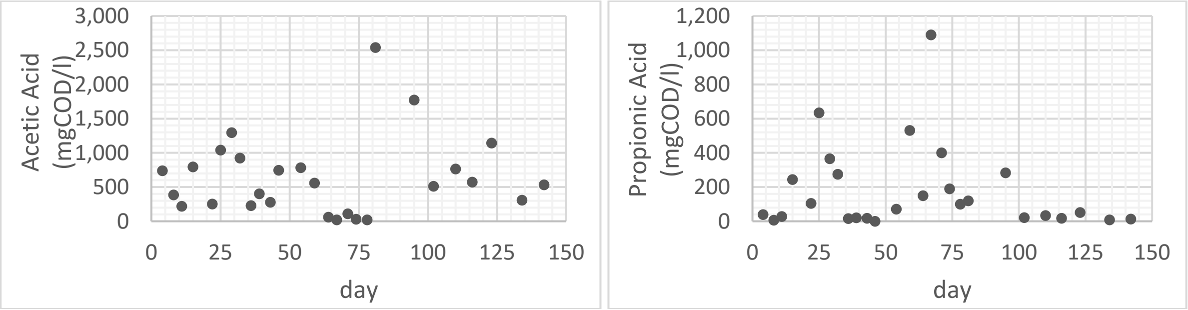

Figure 5: a) Acetic Acid monitoring – b) Propionic Acid monitoring

3.2. *Steady-state and process parameters*

As reported in the previous paragraph, different parameters reached stability at a different time. The starting of the steady state was considered at the day 72. As a proof of the correctness of this choice, the Specific Gas Production (SGP) and the Gas Production Rate (GPR) were calculated every day on basis of the daily gas produced during the previous 26 days, according to the HRT of 26 reached after having stabilised the OLR. Results are shown in Figure 6a and Figure 6b; the trends clearly shown a stabilization of the SGP and the GPR after day 72. The test was so carried on until day 150, after 3 HRT completed.

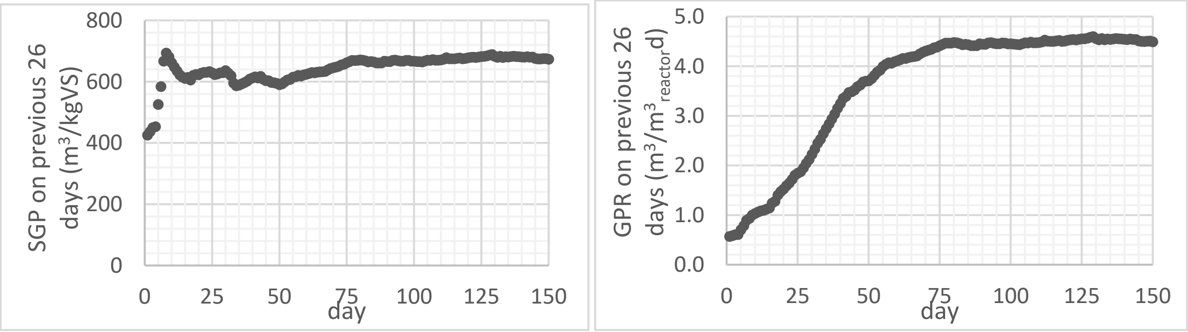

Figure 6: a) Specific Gas Production calculated every day on the previous 26 days, corresponding to a single HRT at the steady state – b) Gas production Rate calculated every day on the previous 26 days, corresponding to a single HRT at the steady state

At the steady state a TS concentration of 83,5 g/kg was observed, with a Volatile Solids (VS) of 49% on TS. An average pH of 7.85 was measured; total alkalinity was 13,840 mgCaCO$_3$/l and partial alkalinity was 12,046 mgCaCO$_3$/l. The difference of the total and partial alkalinity averages at the steady state was 1,794 mgCaCO$_3$/l. The level of total alkalinity detected attests steady state conditions according to Martín-González et al. (2013) [32]. Total VFA was 1,950 mgCOD/l and the characterization is reported in Table 3. Even if steady state is demonstrated by the whole trend of process and stability parameters, VFA concentration at equilibrium is not low. This testifies the presence of biodegradable carbon in solution that must be accounted to foreseen the digestate destiny. Ammonia nitrogen in the digestate liquid fraction was 2.4 g/l, that is the 41% of the total nitrogen accounted in the fed substrate. Ammonia nitrogen is usually referred as one of the main sources of inhibition in AD process, and a typical ammonia inhibition behavior is considered when N-NH$_4^+$ exceeds 1.5-2.0 g/l [33] [34]. Other authors reviewed by Chen et al. (2007) [35] refer however of stability conditions even with higher ammonia concentrations, and the present study confirms this as no signs of inhibitions was observed. Ammonia inhibitions is probably not related uniquely to a limiting concentration, but rather to the ability to conduct an homogeneous OLR increasing and to assure operative stability in order to permit the adaptation of the microorganisms at the equilibrium ammonia concentration. The way the start up was conducted, and the highly methodic feeding every 2 hours 7/7 days that avoided localized shock OLR, was probably key factors to avoid ammonia inhibition. Gas quality monitoring proved an average biogas composition of 61.4% of CH_4 and 38.2% of CO_2. H_2S was also monitored and the average concentration was 358 ppm. As final process parameters an average SGP of 0.674 m^3/kgVS was obtained in terms of biogas, and of 0.414 m^3/kgVS in terms of methane. Those values are slightly lower compared to other experiences especially with wet processes [36],[37],[38], but it is important to underline that the SS-OFMSW was not artificially reproduced but collected as available at a full scale plant. A certain degree of plastic impurities must hence be considered, factor capable to imply a lower gas production when it is referred to the VS fraction. An average GPR of 4.5 $m^3/m^3_{REACTOR}d$ was calculated. In case of full-scale upgrading, a biogas gross production of 116 m^3/t is the reference parameter on the fresh OFMSW. All the average values calculated during the last 3 HRT of steady state are reported in Table 3 with the relative standard deviation.

Table 3: Average of the process stability and the process parameters calculated along 3 HRT at the steady state

Parameter	Measure Unit	Average Value	Standard Deviation
TS	(g/kg)	83.5	±1,8
VS	(g/kg)	41.0	±4.4
VS	(%TS)	49.1%	±4.9%
pH		7.85	±0.14
Partial Alkalinity	(mgCaCO3/l)	12,046	±949
Total Alkalinity	(mgCaCO3/l)	13,840	±1,000
Total VFA	(mgCOD/l)	1,956	±1,210
Acetic Acid	(mgCOD/l)	755	±787
PropioniC Acid	(mgCOD/l)	113	±129
Butirric Acid	(mgCOD/l)	81	±107
Pentanoic Acid	(mgCOD/l)	39	±52
Hexanoic Acid	(mgCOD/l)	834	±1,012
Eptanoic Acid	(mgCOD/l)	97	±96
NH_4^+	(g/l)	2.4	±0.1
CH_4	(%)	61.4%	±2.2%
CO_2	(%)	38.2%	±1.4%
H_2S	(ppm)	358	±136
SGP	(m^3/KgVS)	0.674	±0.043
GPR	($m^3/m^3_{REACTOR}d$)	4.5	±0.3

Results of tests from other authors with similar conditions (mono-digestion of OFMSW with TS of the feeding materials of an average of 20%) are reported in Table 4. It is possible to notice the better performance obtained by the present study both as SGP and as GPR. Only Pavan et al. (2000) [30] obtained similar values of SGP and GPR with pure SS-OFMSW digestion. They however report about not stable process conditions and a possible process failure. They fixed the OLR of 6.0 kgVS/m^3d as the maximum limit for single phase process, and suggested a two-phase digestion approach to evaluate if better stability is possible (condition that would have consequently lowered the GPR of the process). According to those experiences, as an even slightly higher OLR is applied in single phase with stability, agitation efficiency, grade of OFMSW selection and purity, and higher HRT, are recognized the key factors to increase the process performances.

Table 4: Comparison of different OFMSW digestion results, readapted from Bolzonella et al.(2003) [29] (SS-Source Selected; MS- Mechanically Selected)

Author	Ref.	SGP (m^3/kgVSd)	GPR (m^3/m^3)	OLR (kgVS/m^3d)	TS in feed (%)	HRT (d)	Type of OFMSW
This study		0.67	4.5	6.2	20.5	26	SS- + MS-
Bolzonella et al. (2003)	[29]	0.23	2.1	9.2	20	13.5	MS-
Cecchi et al. (1991)	[39]	0.26-0.40	2.5-4.1	5.9-13.5	16-22	8-15	MS-
Mata-Alvarez et al. (1993)	[40]	0.32-0.37	3.1-6.1	9.7-17.8	18-25	8-12	MS-
Vallini et al. (1993)	[41]	0.30	4.1	13.5	22	7.8	MS-

Pavan et al. (2000)	[30]	0.32	3.1	9.7	25	11.7	MS-
Pavan et al. (2000)	[30]	0.78	4.9	6.0	10	11.8	SS-
Scherer et al. (2000)	[42]	0.22	5.7	7.6	16	18	MS-
Bolzonella et al. (2006)	[9]	0,71	3.2	4-6	33	40-60	SS-

4. Conclusions

The research demonstrates that the OFMSW can be treated in a mesophilic PFR fermenter with an elevate OLR of 6.2 kgVS/m^{3}d and without any dilution or co-substrates addition. The mixing system must assure full homogeneity in the fermenter. Sedimentation must severely be avoided to allow full exploitation of the entire fermentative volume. Mixing system must also be able to avoid formation of floating layers or crusts, in order to assure smooth spill and release of the methane, that would otherwise be toxic for the biological system. TS reached at the steady state was 8,4% and it does not permit to refer as a Semi-Dry process (10-15% TS) .The density of the digestate could potentially however cause troubles of mixing efficiency if a normal propelled agitation system is adopted. The process results stable as single stage reactor, no needs of digestate recirculation was detected. The elevate load resulted in a SGP of 0.67 m^3/kgVS in terms of biogas, and of 0.41 m^3/kgVS in terms of methane. The low reduction of SGP respect to low solids wet digesters (where SGP of SS-OFMSW is usually > 0.7 m^3/kgVS) was justified by a high GPR, that was found to be 4.5 m^3/m^{3}d as average on 3 HRT of process stability, so it is considered a good balance between energy extraction and digester size. These results encourage the treatment of sole OFMSW, without necessity of dilution (with water or wastewater) or co-substrates (lignocellulosic materials), and the diffusion of relatively small plants. A proper composting technology to transform the digestate in quality compost must however been foreseen. Improvement in the tested scenario could be obtained by using an SS-OFMSW with higher TS content, but it would be related to the availability of a pre-treatment system able to actuate an efficient impurities removal without reducing the original TS content of the OFMSW. With the same digesting volume and OLR, this would lead to a higher HRT that could be useful for enhancing the SGP. An increased HRT would also probably help to decrease the steady state VFA concentration, detail that would make the subsequent digestate composting easier. Future investigation on rheology could also be useful to understand the mixing attitude of the digestate and to support the design of a proper agitation system.

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