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Anaerobic digestion of municipal solid wastes: Dry thermophilic performance

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ABSTRACT

The purpose of this study was to analyze the performance of two laboratory-scale reactors (5.0 L) treating organic fraction of municipal solid waste (OFMSW): source sorted OFMSW (SS_OFMSW) obtained from a university restaurant and mechanically selected municipal fraction (MS_OFMSW) obtained from a Municipal Treatment Plant placed in Cadiz-Spain. Discontinuous reactors operated at thermophilic (55 °C) and dry (20% total solid) conditions. Different decomposition patterns were observed: (1) the SS_OFMSW exhibited the classical waste decomposition pattern with a fast start up phase beginning within 0–5 days and 20–30 and a subsequent stabilization phase. The VS removal was 45% with a cumulative biogas of 120 L in approx. 60 days; (2) the MS_OFMSW showed a methanogenic pattern throughout the whole experimental period (60 days) and this gave higher levels of organic biodegradation (56%VSr) and biogas production (82 L). Both processes were completed and a high level of cumulative methane production was achieved in less than 60 days, proximally 25–30 L.

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1. Introduction

The data published by the National Plan of Urban Wastes (2000–2006) in Spain indicates that 40–45% of total municipal solid wastes (MSW) are organic fraction of municipal solid waste (OFMSW). Anaerobic digestion is an attractive treatment strategy for MSW and shows great interest from an environmental point of view and for society benefit by providing a clean fuel from renewable feedstocks. Also, several research groups have developed anaerobic digestion processes using different organic substrates (Pérez et al., 1997, 2005; de la Rubia et al., 2006; Forster-Carneiro et al., 2007a).

The biometanization of organic wastes is accomplished by a series of biochemical transformation, which can be toughly separated into a first step where hydrolysis, acidification and liquefaction take a place and second step where acetate, hydrogen and carbon dioxide are transformed into methane. In the case of food waste from restaurants or markets, the reactions of the digester and the bacterial population could be determined by the nature of the feedstock (complex substrate with different composition and origin) (Chynoweth, 1987). Also, there are a large number of factors which affect biogas production efficiency such as environmental conditions like pH, temperature, inhibitory parameters like high organic loading, formation of high volatile fatty acids, inadequate alkalinity, etc. Volatile solids input, digester temperature and retention time are operational parameter that have a strong effect on digester performance.

In recent years, a number of novel reactor designs have been adapted and developed allowing a significantly higher reaction rate per unit of reactor volume. Basically, the difference of the process is the way the microorganisms are retained in the bioreactor, and the separation between the acidogenic and the methanogenic bacteria which reduce the anaerobic digestion limitations (Chynoweth et al., 2001).

The anaerobic digestion of OFMSW reply on one-stage system (Lissens et al., 2001), and corresponding to 90% of Europe full scale plants. In the system the reactions take place simultaneously in a single reactor, and it have simpler designs suffer less frequent technical failures and have smaller investment costs. Biological performance of one-stage system is, for most organic wastes, as high as that presented by two stage systems if the reactor has a good design and the operational conditions are carefully chosen.

Several new approaches repeated about the efficiency improvement of semi-dry anaerobic digestion and dry digestion process (20–35% TS), where no or little water, or sludge, could be added to the organic urban wastes (Pavan et al., 1994; Bolzonella et al., 2003). In addition, some systems have been designed to operate at thermophilic conditions (55 °C) for to accelerate anaerobic digestion (Hartmann and Ahring, 2006). Thermophilic operations are a reliable and acceptable option for digestion of organic urban wastes (Kim et al., 2002; Kuo and Lu, 2004).

The purpose of this study was to analyze the performance of a laboratory-scale reactor (5 L) operating with two different organic fractions of municipal solid wastes (OFMSW): (a) source sorted

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OFMSW (SS_OFMSW) from a university restaurant and (b) mechanically selected OFMSW (MS_OFMSW) from the Treatment Plant "Calandrias" in Spain. The interest was the selection of a flow-model to describe the hydrodynamic pattern in the reactor, and to obtain an efficiency conversion of SS_OFMSW or MS_OFMSW to biogas, in 60 days.

2. Methods

2.1. Experimental device

The assays were carried on batch laboratory-scale reactor with total capacity of 5.0 L. The cover of each reactor incorporated five separate ports for different functions: pH control; mechanical agitation system; measurement of the biogas generation (and composition, using Tedlar bag, 40 L); temperature control by means of recirculation of the internal liquid; taking liquid samples. This configuration allowed operating under high-solids conditions without any hindrance to the leachate circulation and without the use of mechanical devices for maintenance. This continuous flow reactor was based on the attainment a good contact between the biomass and the effluent for the development of a balanced process.

2.2. Substrate preparation

The unsorted and fresh organic fractions and inoculum source selected for using in discontinuous reactor were as follows:

(1) Separately select biowaste fraction (SS_OFMSW) obtained from a university campus restaurant (Cádiz-Spain). The pre-treatment of the SS_OFMSW was required to provide a suitable refined digested material (selection, drying, crushed and homogenization of particles size of 2–6 mm), in accordance with Forster-Carneiro et al. (2004).
(2) Mechanically selected municipal fraction (MS_OFMSW) obtained from the Municipal Treatment Plant "Calandrias" located in Jerez de la Frontera (Spain).
(3) Mesophilic digested sludge (SLUDGE) was obtained from the "Guadalete" Wastewater Treatment Plant, located in Jerez de la Frontera (Spain) and was used as inoculum. It is coming from the recirculation line of mesophilic anaerobic digester.

All reactor vessels (SS_OFMSW or MS_OFMSW reactor) were loaded with raw feedstock and inoculated with mesophilic municipal sludge (30%). Water was added to obtain the desired total solid percentage (20%ST) in accordance with Forster-Carneiro et al. (2007b).

The initial physical and chemical characteristics of OFMSW and inoculums used in this study are given in Table 1. The SS_OFMSW is a high-solids substrate, with an average organic content of 77.7% (measured by VS) – value that are significantly higher than MS_OFMSW (43.0%). The majority of the total solids present in the SS_OFMSW were volatile organic solids. The readily biodegradable organic matter in food waste with high moisture contents enhanced the biological activity and showed the viability of anaerobic digestion. The MS_OFMSW contained a large amount of inorganic material, mainly from soil/sand and small inorganic material. Digested SLUDGE is biodegradable and homogeneous inoculum used with success in previous works (Forster-Carneiro et al., 2004). The initial characteristics of SLUDGE were 7.9 of pH, 16.6 g/L of DOC and a high C/N ratio (15.7).

2.3. Analytical methods

The parameters analyzed for the characterization of substrates were as follows: density, total solids (TS), volatile solids (VS), fixed solids (FS), total suspended solids (TSS), volatile suspended solids (VSS), fixed suspended solids (FSS), pH, alkalinity, total nitrogen Kjeldahl (TNK), total acid, ammonia nitrogen (AMON-N), total organic carbon (TOC) and chemical oxygen demand (COD). Daily analyses were performed on the leachate from both reactors A and B: TS, VS, FS, COD, DOC, pH, alkalinity, amon-N, and the biogas production and composition.

Determining the following quantities monitored the digestion process: TS, VS, and FS, pH, alkalinity, TKN, Amon-N, COD, TOC, Total acid and composition and production of biogas. All analytical determinations were performed according to "Standard Methods" (APHA, 1989), after the drying, grinding and dilution of the samples. This procedure is more representative due the semi-solid characteristic of the substrate (except for TN, TS, and VS that is not necessary to dilute the samples) (Guitian and Carballas, 1975).

The alkalinity of each sample was analysed using a COMPACT TITRATOR S+ (Crison Instruments S.A.). The TOC and DOC analyses were carried out using a SHIMADZU 5050 TOC Analyzer for combustion-infrared (5310B) from the "Standard Methods".

Total acid concentration was calculated by addition of individual volatile fatty acid levels (VFA). The fatty acid levels were determined by gas chromatography – SHIMADZU GC-17A equipped with a flame-ionization detector and capillary column filled with Nikol (polyethylene glycol modified by nitroterephthalic acid). The injection port and detector temperatures were 200 °C and 250 °C, respectively. Helium was the carrier gas at 50 mL min^{-1}. The nitrogen flow rate was 30 mL min^{-1}. Total VFA was calculated by the addition of individual VFA levels.

Gas produced in the reactor was collected in a 40 L Tedlar Bag. The volume of biogas was measured directly using a WET DRUM TG 01 (mbar) high precision gas flow meter through a CALI 5 BOND^{TM} meter displacement bag. Biogas samples were obtained daily and then analysed by gas chromatographic separation

Table 1
Initial mean characteristic of the organic wastes and initial waste of the reactors

Parameter	OFMSW		Inoculum	Initial waste reactor	
	Food waste (SS_OFMSW)	Solid waste (MS_OFMSW)	Mesophilic sludge (SLUDGE)	SS_OFMSW	MS_OFMSW
Density (kg/m^3)	500.0	295.0	1100.0	1080.0	1100.0
Total solids (%)	89.8	17.2	3.9	21.1	19.2
Volatile solids (%)	69.8	7.4	2.6	17.0	9.8
pH	7.6	7.9	7.9	6.2	7.1
Alkalinity (g/L)	0.1	0.09	0.5	0.2	0.3
Amon-N (g/L)	0.1	0.3	3.0	1.8	3.1
TNK (g/kg)	12.8	26.0	25.4	24.0	29.0
Total acid (g/L)	0.5	2.0	3.3	0.3	0.6
DOC (g/L)	49.9	39.7	16.6	63.6	50.8
COD (g/L)	31.9	41.3	16.3	65.6	54.3
C:N	35.4	11.9	15.7	19.5	10.1

(SHIMADZU GC-14B) using a stainless steel column packed with Carbosieve SII (3.2 mm diameter and 2.0 m length) and a thermal conductivity detector (TCD). A standard gas (from Carburos Metálicos S.A.) was used to calibrate the system and this had the following composition: 4.65% H_2; 5.3% N_2; 69.9% CH_4 and 20.1% CO_2).

3. Results and discussion

3.1. Hydrodynamic characterization of the reactor

Previously to develop the experimental design, a lab-study was carried out in order to determine a flow-model able to describe the hydrodynamic of the reactor (5.0 L). The experiment was carried out to determine the curves of distribution of residence times by means of application of the experimental stimulus-answer technique. The application and determination of the flow-model will allow describing the hydrodynamic behaviour and the yield of the reactor designed by the group.

The theoretical half residence time is bigger than the experimental half residence time. These results suggest that the reactor is of upset tank with a certain dead volume, by-pass or recirculation that it causes this distortion in the flow. Following the departure hypothesis, the corresponding adjustments were carried out with the most two parameters models used: the Levenspiel models (1981) and the Cholette–Cloutier model (1959). The results obtained suggest that the pattern of Levenspiel could be used to describe the hydrodynamic behaviour of the used reactor: 98.90% of total volume of reactor is completely mixed, and only 1.10% is of pug-flow.

3.2. Performance of start up strategy in SS_OFMSW and MS_OFMSW reactor

Table 1 summarizes the characteristics of each reactor. The analytical parameters indicated high biodegradability of the complex substrates. The initial characteristics of SS_OFMSW and MS_OFMSW were 63.6 and 50.8 g/L of DOC, 24.0 and 29.0 g/kg of TNK, respectively. The carbon and the nitrogen, indispensable for the growth and the diversification of the biomass, was analyzed, the results were 19.5 and 10.1 for SS_OFMSW and MS_OFMSW, respectively. These results suggest a higher concentration of ammonia nitrogen and smaller percentage of organic carbon of the MS_OFMSW.

Table 2
Methane yield of SS_OFMSW and MS_OFMSW reactor after 60 days of experiment

60 days	Organic matter removal (%)			Biogas production		Accumulative (L)	
	VS	COD	DOC	(L/day)		Biogas	Methane
SS_OFMSW	45.0	29.9	30.3	3.0	0.6	120.0	25.0
MS_OFMSW	55.5	59.3	64.1	2.0	0.7	82.0	29.9

The bioprocess efficiency profiles of organic matter were shown in Fig. 1 (as total and volatile solids evolution and as COD and DOC evolution and removal). As can be seen, the initial total solid concentrations in both reactors were approx. 20.0 g TS/L. For SS_OFMSW reactor, both TS and VS values showed slow and constant decrease since the first day, obtaining total and volatile solids removal of 34.7%TS and 44.2%VS and 55.0% of COD or DOC elimination, after 60 days of experiment (Fig. 1A). In the case of the MS_OFMSW, the reactor showed higher organic matter elimination, expressed as SV, DOD or COD (Fig. 1B). After 60 days, in the MS_OFMSW reactor the biodegradability was 55.5%VS, or 64.1% DOC elimination (Table 2). These results can be related with the different nature of the wastes in the study, that it conditioned the biodegradation. For SS_OFMSW reactor, the pH control was necessary with hydroxide of sodium (6 N) during the first 10 day and for MC_OFMSW reactor during the first week. Fig. 2 showed

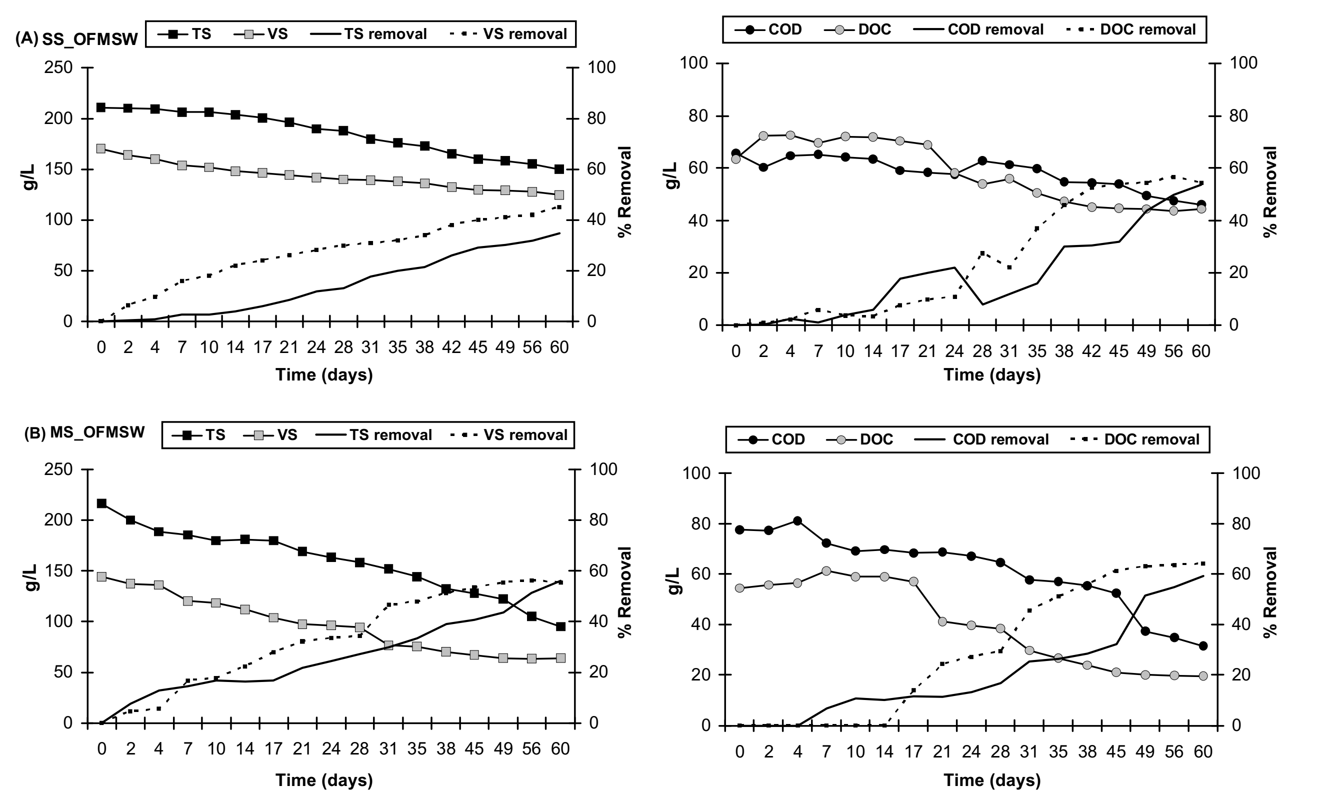

Fig. 1. Temporal evolution for SS_OFMSW in (A) and MS_OFMSW in (B): total solids (TS), volatile solids (VS), chemical oxygen demand (COD) and dissolved organic carbon (DOC); and removal percentages after 60 days of experimentation.

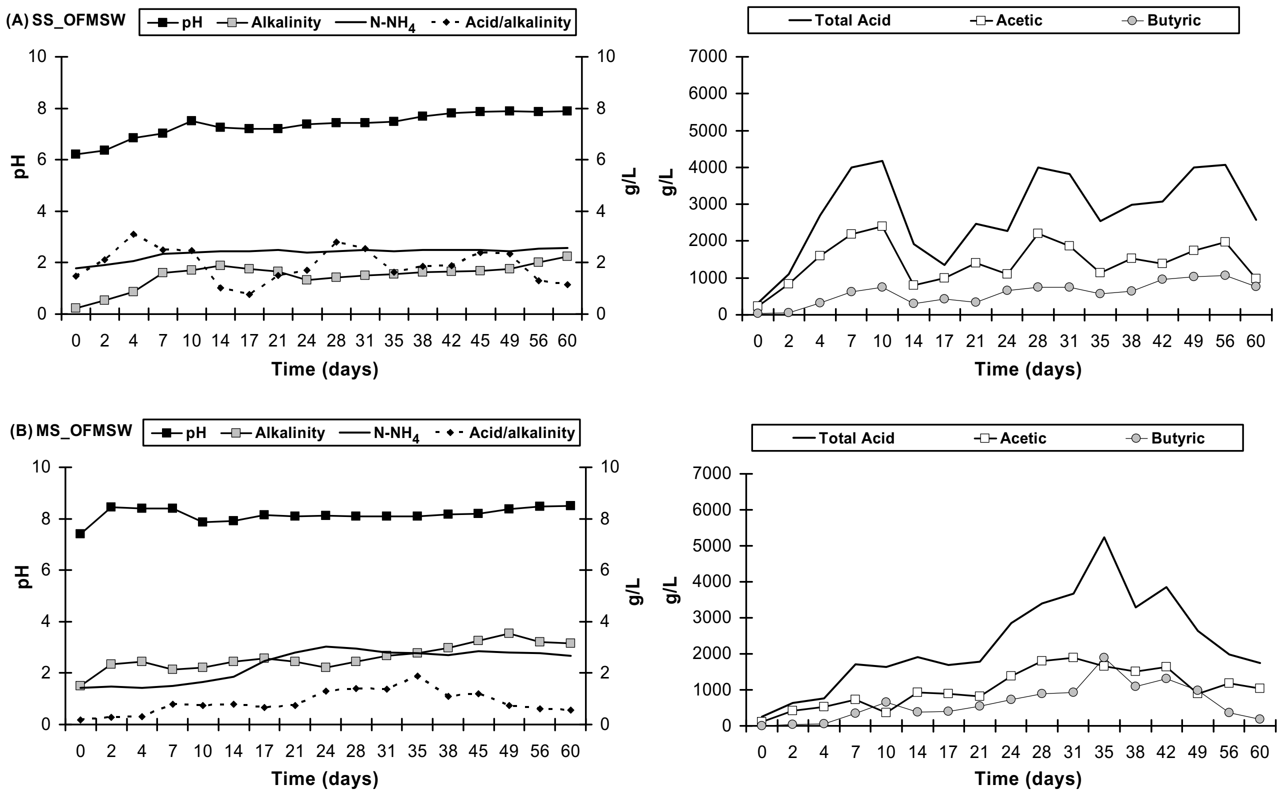

Fig. 2. Temporal evolution for SS_OFMSW in A and MS_OFMSW in B: of pH, alkalinity (CaCO3, g/L), N-amon (N-NH4 g/L), acid/alkalinity; and total acid and VFA (butyric and acetic), after 60 days of experimentation.

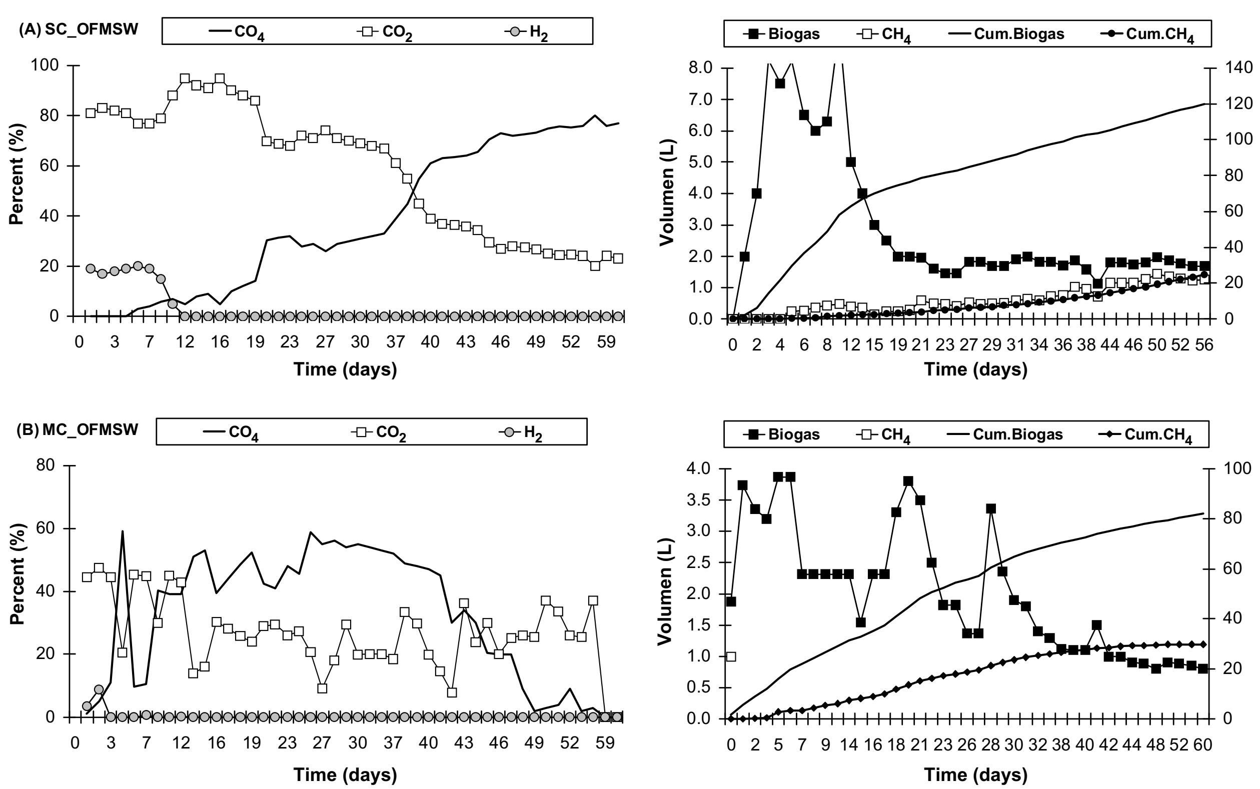

Fig. 3. Temporal evolution for SS_OFMSW in A and MS_OFMSW in B: (a) biogas composition; (b) biogas and methane generation and cumulative after 60 days of experimentation.

the temporal evolution of pH, alkalinity, $N-NH_4$, acid/alkalinity ratio, total acid and VFA (butyric and acetic) for SS_OFMSW and MS_OFMSW. For the OFMSW reactor, the hydrolytic phase take place in the first two weeks and it is characterized by the increase of the ammonia levels from 1788 up to 2400 mg/L and the increase of alkalinity from 221.4 up to 1698.0 mg/L (Fig. 2A). These results were indicative of a higher microbiologic activity with a great increment of the acidity of the means favoured by the hydrolysis of the organic compounds. In the case of the MS_OFMSW, the reactor showed adequate alkalinity and ammonia levels to maintain a stable pH in the digester for optimal biological activity until day 25, coinciding with the stable phase of the digestion. These results are related with the total acid concentration that continuously increases until 5000 mg/L at the day 38 of experiment; after this, total acid concentration decrease until reaching values of 1800 mg/L at the end of the experiment (Fig. 2B).

In the SS_OFMSW reactor the highest total acid concentration is observed in the start up phase between the day 1 and 15; high molecular weight compounds are converted into intermediate VFA, mainly propionic and butyric acids by acidogenic bacteria. Acetic acid, the major intermediate in methanogenesis is formed through the degradation of propionic and butyric acids and through the oxidation of hydrogen, process involving different acetogenic populations. Also, while the methanogenesis and methane gas production increased, the carbon dioxide and VFA concentrations decreased. For MS_OFMSW reactor this high production of total acids was not observed. The highest total acid concentration was observed in the stable phase after the day 25. These results have been also observed in the production and composition of the biogas.

Fig. 3 showed the temporal evolution of biogas composition, biogas and methane generation and cumulative for SS_OFMSW and MS_OFMSW. As can see in the Fig. 3A, for SS_OFMSW reactor the initial methane production increased when the production of hydrogen (20% of total volume of biogas) decreased. The higher daily generation was 5.6 L/day in the first 15 days and 3.0 L/day at the end of the experiment (Table 2). The corrected cumulative biogas and methane yield from SS_OFMSW reactor showed a fast increase in the first 10 days with maximum values of 58.0 and 1.8 L, respectively. After the day 20, the process is characterized by methanogenic phase or stable phase, where the acidity continuously increases, fundamentally due to butyric acid. Methane can only be generated by specific methanogenic bacteria which use acetic acid or hydrogen. The produced biogas has an average methane concentration of 53.4% during the stabilization phase (20–60 day). The cumulative biogas and methane yield of SS_OFMSW reactor showed a slowly increase, day after day, until reaches maximum values of 120.0 and 25.0 L, respectively.

MS_OFMSW reactor (Fig. 3B) showed an initial increase of methane generation starting from the day 5 coinciding with the decrease of dioxide of carbon and hydrogen gases. Between the days 5 and 40, constant values of methane were observed (44.8%) and dioxide of carbon (55.2%), indicating stable phase. In this period, the highest daily generation was 2.5 L/day. The corrected cumulative biogas and methane yield from MS_OFMSW reactor showed a fast increase from the first day of experiment with maximum values of 82.0 L and 29.9 L, respectively. In this case, the chronological difference between the acidogenic, acetogenic and methanogenic phases is not easily visible. The MS_OFMSW showed methanogenic behaviour during all experiment.

The final products of anaerobic degradation of OFMSW are methane, carbon dioxide, other trace gases amounts as hydrogen sulphide and hydrogen, and humus. Studies reported in this paper have shown that the hydrogen sulphide concentrations were null and it is not detected because the precedent food waste of the restaurant doesn't contain any sulphur.

4. Conclusions

Two different decomposition patterns were observed for two different municipal solids wastes: (1) the SS_OFMSW exhibit the classical waste decomposition pattern with a fast start up phase beginning within 0–5 days, an acclimation stage (acidgenic/acetogenic phases) between days 5 and 20–30 and a subsequent stabilization phase; (2) the MS_OFMSW showed a methanogenic pattern throughout the whole experimental period and this gave higher levels of organic biodegradation and methane production.

Under these conditions the performance of SS_OFMSW was a VS removal of around 45% (or approximately 55% DOC removal) and cumulative biogas of 120.0 L. In contrast, MS_OFMSW performance was 56%VS removal (or approximately 65% DOC removal) and cumulative biogas of 82.0 L. Both processes were completed and a high level of cumulative methane production was achieved in less than 60 days, proximally 25–30 L.

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