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Pilot Plant Data Assessment in Anaerobic Digestion of Organic Fraction of Municipal Waste Solids

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Abstract: In this paper, a preliminary study of anaerobic digestion of organic fraction of municipal solid wastes (OFMSW) in presented with the aim to compare the performances of both wet- and dry-type reactors. The treatment of OFMSW via anaerobic digestion (AD) producing biogas is a process that is receiving a growing interest because two different needs can be coupled: the request of sustainable municipal waste treatments and increasing demand renewable energy. This paper aims to offer experimental results comparing batch test and continuous experimental reactors under different conditions of humidity and solid content. Results show that both the investigated configurations may be used for converting OFMSW into a high quality biogas and that the increase of dry matter in the continuous process still allows to achieve significant biogas production rates. A slight reduction of the methane content was observed (less than 5% relative) that can be also related to the change in the level of volatile fatty acids. These results are very promising in supporting the possibility of operating an industrial scale plant with a dry-process without affecting the system performance.

Keywords: municipal waste; biogas; wet anaerobic digestion; dry anaerobic digestion

1. Introduction

The management of municipal solid waste represents represent one of most actual challenges also in the view of sustainable economy for future generations [1,2]. Since the origin of the waste significantly affects the composition, along with the location of the urban sites where the waste is produced [3–5], the management of this complex system is a very challenging issue [6–8]. In addition, the food consumption and chemical composition changes [9] due to technological steps forward in the food industry, makes the municipal solid waste treatment a very important issue [10] that can be tackled in different ways: from energy valorization via thermal treatments [11] to more sustainable biological ways to recover energy value [12].

Along with this problem, humankind has to face serious environmental and energy problems due to the energy-intensive lifestyle that has emerged in developed countries over the last century [13–20]. In this regard, sustainable conversion of waste to energy or chemicals is considered a reliable way to solve two problems once: reducing the amounts of non-recyclable and non-reusable waste and producing a significant amount of energy and/or chemicals in order to satisfy increasing demand.

In this regard, production of bio-methane via waste conversion is a strategy to strongly increase the sustainability of several processes, from energy to chemical production. In fact, methane can be used as fuel for energy generation or as feedstock for the production of CO and H_2, used as reactants in several chemical processes [21–25].

In recent decades, several technologies have been proposed to convert waste into energies that can be classified in (i) thermal, (ii) chemical, and (iii) biochemical conversion. Thermal conversion of waste—such as incineration, gasification, and pyrolysis—recovers energy by adopting high temperatures [26–29].

The chemical conversion of waste mainly involves esterification reaction of fat with alcohol (methanol or ethanol) producing mono-alkyl esters that can be used as efficient additives for diesel fuel (biodiesel) [30,31].

Finally, with biological conversion technologies the waste is transformed into high-value products by utilizing microbial processes. Such a process therefore is restricted to biodegradable waste only, such as food and livestock or agricultural waste [32].

In particular, anaerobic digestion (AD) of organic waste is a biological process in which organic waste is mainly converted into methane and carbon dioxide in the absence of oxygen [33,34]. A complex reaction mechanism occurs in such transformation and several bacterial species are involved. Briefly, anaerobic digestion consists of four main phases such as (i) hydrolysis, (ii) acidogenesis, (iii) acetogenesis, and (iv) methanogenesis. During hydrolysis, organic polymers—mainly carbohydrates—are converted to simpler molecules such as monosaccharides, amino acid, and fatty acids. Such molecules are converted into volatile fatty acid (VFAs), carbon dioxide, ammonia, and hydrogen by acidogenic bacteria. After that, acetogenic bacteria are able to transform VFAs into acetic acid, that is converted into methane during the methanogenesis step. The biogas that is formed mainly consists of methane and carbon dioxide and traces of some other species such as ammonia, sulfidic acid, and VFAs. Such gas can be used as fuel for in situ energy generation—i.e., electricity, heat—or can be upgraded for obtaining highly pure methane for either chemicals processes (such as steam reforming to produce syngas), or domestic uses as fuel. Residual digestate is further treated usually in aerobic reactors (i.e., biocells), aiming to obtain a pathogen free compost that can be used as fertilizer. Depending on waste type, several technologies have been proposed in recent decades. In fact, AD can be performed at low temperature as 30–45 °C (mesophilic AD) or higher temperature as ca. 55 °C (thermophilic AD) [34]. When high temperatures are used, a faster production of biogas is observed even if a higher energy consumption is required. Depending on the water content AD is classified in wet (<10% dry matter), semi-dry (10–22% dry matter) and dry (>22% dry matter) systems. Dry-type is usually more convenient than wet-type technology because of the higher biogas production per unit of waste and of the lower energy consumption required, since less water needs to be heated. On the other hand, wet-type offer the advantage in terms of pumping and mixing of the feedstock lowering the installation/maintaining costs of the plant. Finally, AD can be carried out in continuous flow or stirred batch reactors depending on both the amount and the type of waste to be treated [35,36]. Therefore, several aspects have to be taken into account for waste-to-biogas conversion [37,38] and, during recent decades, unlike wet-type, dry-type system has received less attention. For this reason, in this paper, dry-type anaerobic digestion of organic fraction of municipal solid waste (OFMSW) was assessed in a pilot-scale continuous reactor in order to give new insights about such processes for waste-to-biogas conversion.

2. Materials and Methods

Anaerobic digestion was performed in both wet-type and dry-type configuration. In particular, wet-type anaerobic digestion was carried out (see Figure 1) in a battery of five batch reactors (volume, 5 L) equipped with stirrer and sampling system connected to analytical measurements. Temperature was controlled by using a thermostatic bath equipped with a temperature controller. The feed was changed by using a mixture composed by agro-zootechnical (AZ) digestate (5 kg) and a different amount (0, 100, 125, 150, 175, and 200 g) of biodegradable organic fraction of municipal solid wastes (OFMSW) provided by Calabra Maceri & Servizi S.p.A. (Rende, Italy). When this fraction is zero, this means that the only organic load in the treated biomass comes from the AZ digestate.

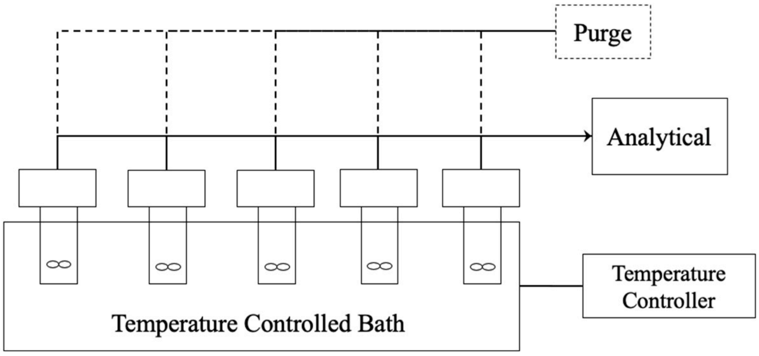

Figure 1. Batch reactors experimental set-up.

The physical and chemical properties of the OFMSW are reported in Table 1 and the biomass was free of metals (according to EN 136587-204) with a solids content of about 27 wt %.

Table 1. Biodegradable OFMSW composition

pH (-)	TOC (%)	Density ($kg \cdot m^{-3}$)	Dry Residue @105 °C (% mass)	Dry Residue @ 550 °C (ppm)
7.3–7.7	24–25.9	830–1030	38.2–39.7	4.2–4.8

Chemical-physical characterization of investigated OFMSW revealed that it contains about 31 wt % of total solid which contains about 72% of volatile solids. The temperature of the reactors was kept at constant value of 55 °C. Such experiments allowed to obtain insights about the productivity of methane from investigated OFMSW during wet-type anaerobic digestion. In order to monitor the effect of volatile organic acids on the process evolution the FOS/TAC [39] ratio was determined by means of an automatic titration device (Hach Lange TIM 840) as a two-step endpoint titration using a sulfuric acid solution having a substrate concentration of 1 mol/L [40].

Figure 2 shows the experimental setup for dry-AD in continuous flow configuration.

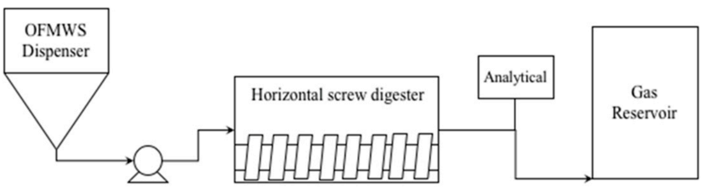

Figure 2. Pilot plant for dry-type anaerobic digestion in continuous configuration.

The continuous reactor consists of a parallelepid (300 cm in length, 80 in height, and 80 in depth) in steel. In the lower part there is a rotating axis (diameter 10 cm) with small blades that provides to mix the biomass in digestion. The temperature is controlled through a series of electric plates placed in the lower area which act on the external surface of the reactor through an oil bath. The OFMSW as biomass was fed using a 350 L hopper provided with screw auger due to the high viscosity of the material. The gas-phase stream was collected in a gasometer and the amount of methane measured via an analyzer (Optima 7, MRU Instruments Inc., Humble, TX, USA). The investigated OFMSW was previously hashed and mixed obtaining a homogenous mush (see Figure 3) containing a total amount of solid matter higher than 25%.

Figure 3. Mushed and mixed OFMSW used as feed for the dry-AD.

3. Results

The effect of OFMSW content on biogas productivity as a function of time during wet-AD in batch reactor is reported in Figure 4. Data clearly show these discontinuous reactors require a certain induction time to reach significant gas productivity. From the data of Figure 4 two interesting evidences can be found: (1) The induction period is shortened below two days when a minimum fraction of OFMSW is added to the system. In fact, only the run feed with only with AZ Digestate exhibited a delay time in gas productivity of about 7.5 days. (2) The gas production growth is directly related to the amount of organic added in the OFMSW. In particular, Figure 5 shows that the biogas final productivity (namely after 32 days reaction) linearly depend on OFMSW content.

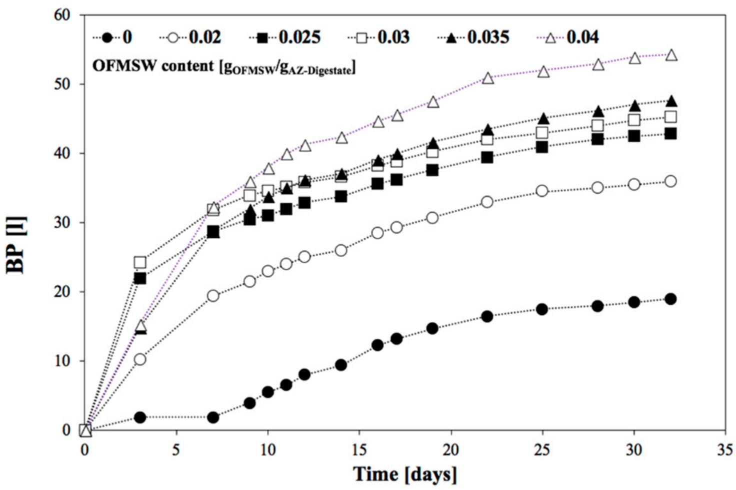

Figure 4. Biogas productivity as a function of reaction digestion time during batch wet-AD of agro-zootechnical (AZ) digestate containing a different tenor of OFMSW.

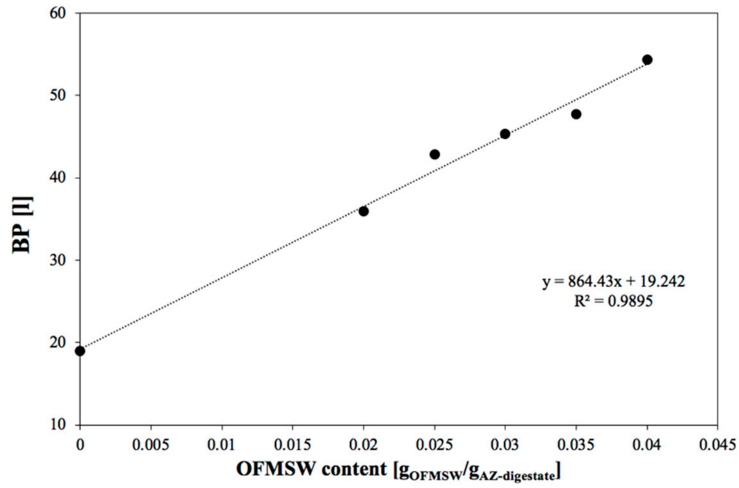

Figure 5. Effect of OFMSW content on biogas productivity during batch wet-AD.

During this set of experiment the value of FOS/TAC was always around 0.3, indicating a quite stable operating condition.

By using linear regression, the following linear model is derived

$$BP = 864.4 \cdot OAZ + 19.2 \quad (1)$$

where BP is the biogas productivity in l after 32 days of AD and OAZ is the OFMSW/AZ-digestate ratio expressed as g/g. This suggest that the feedstock composition is of paramount importance for the process and that higher is the amount of OFMSW higher is the biogas production. In order to better evaluate the effect of OFMSW on biogas production, the specific net productivity of biogas (BSNP) was calculated as

$$BSNP = (BP - BP0)/W\_OFMSW \quad (2)$$

where BP is the biogas productivity expressed in l, BP0 is the biogas productivity of AD of digestate without OFMSW expressed in l, and W_OFMSW is the amount of OFMSW expressed in kg. As reported in Figure 6, BSNP strongly increases during the first seven hours and then decreases even if such decrease is more important for the systems having a OFMSW/AZ-digestate weight ratio of 0.025 and 0.03.

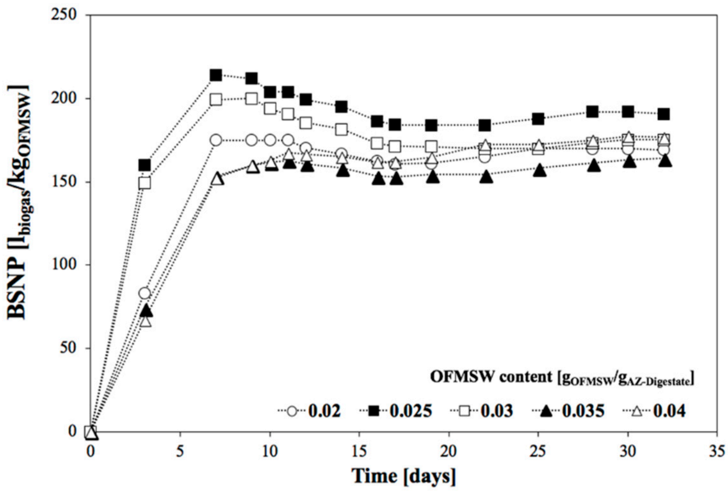

Figure 6. Biogas specific net productivity as a function of reaction digestion time during batch wet-AD of agro-zootechnical (AZ) digestate containing a different tenor of OFMSW.

The obtained trend indicates that the system with a OFMSW/AZ-digestate weight ratio equals to 0.025 is the most performant system in terms of conversion of OFMSW to biogas since it exhibits a higher value of BSNP in the entire digestion period [41–43]. Obviously, not only chemical composition but even physical properties of the feed—such as viscosity, density, etc.—should be taken into account in order to better investigate the phenomena occurring during the process and better rationalize the obtained data.

As previously described, dry-type AD of OFMSW was carried out in a horizontal reactor (see Figure 2) keeping a residence time of about one month. The plant start-up was carried out in wet-type configuration (ca. 14 wt % solids) by mixing OFMSW with municipal waste leachate (leachate properties: pH = 5.04, COD = 86,630 mg/l; solid content = 8.4 %) which was gradually reduced aiming to obtain a feed with an amount of solids of about 27 wt %. The results are summarized in Table 2.

Table 2. Biogas production during wet- or dry-type AD of OFMSW in a continuous reactor

Solid Content (wt %)	Biogas Productivity (m^3/day)	CH_4 (vol%)	H2S (ppm)
14	7.8	58.4	276
27	9.2	56.8	258

The results clearly show that the biogas productivity clearly increases with no appreciable influence on biogas composition, from wet-type to dry-type configuration. In fact, by passing from wet-type to dry-type configuration, the biogas productivity increases from 7.8 to 9.16 m^3/day while the quality of biogas decreases from 58.4 to 56.8 %CH_4. In the case of 14 wt % of solid content, the value of FOS/TAC was stably found around 0.3 whilst the FOS/TAC value decreased around 0.2 when the solid content was increased to 27 wt %. Therefore, we should also consider this parameter as negatively affecting the biogas quality. After the reaction, the solids content in the digestate decreased to about 8 wt % indicating that about 70% of OFMSW was converted into biogas.

4. Conclusions

In this paper, the biogas production via anaerobic digestion (AD) of organic fraction municipal solid waste (OFMSW) in both wet- and dry-type configuration was assessed. The obtained data from the preliminary bench-scale wet-AD of OFMSW/digestate mixture confirmed that the investigated OFMSW is a suitable biomass to be used in anaerobic process also combined with agro-zootechnical digestate. Favorable effect was found on biogas productivity when increasing the organic load from the OFMSW. Dry-AD was carried out in a pilot plant equipped with continuous reactor by feeding OFMSW/leachate mixture with a solid content higher than 25 wt %. Results clearly show that, under optimized conditions, the dry-process (solid content 27 wt %) can be a suitable alternative for industrial application of anaerobic digestion process of organic fraction of municipal solid waste. Without losing on biogas production efficiency, the reduction of the water amount allows different benefits such as lower amount of digestate to be treated hereafter and reduced process volume with the gas productivity.

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