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Scale effect of anaerobic digestion tests in fed-batch and semi-continuous mode for the technical and economic feasibility of a full scale digester

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HIGHLIGHTS

- CH_4 production capacity of vegetable waste was assessed on different scales and modes.
- CH_4 yield from the pilot scale test was about 80% of that from the smaller scale test.
- Produced net electricity was from 30% to 50% of the food industry plant consumption.
- Available thermal energy can cover from 10% to near 100% of the plant requirement.

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ABSTRACT

Methane production capacity in mesophilic conditions of waste from two food industry plants was assessed in a semi-pilot (6 L, fed-batch) and pilot (300 L, semi-continuous) scale. This was carried out in order to evaluate the convenience of producing heat and electricity in a full scale anaerobic digester. The pilot test was performed in order to obtain more reliable results for the design of the digester. Methane yield, returned from the pilot scale test, was approximately 80% of that from the smaller scale test. This outcome was in line with those from other studies performed in different scales and modes and indicates the success of the pilot scale test. The net electricity produced from the digester accounted for 30–50% of the food industry plants' consumption. The available thermal energy could cover from 10% to 100% of the plant requirements, depending on the energy demand of the processes performed.

1. Introduction

Italian food industry, with a sales volume of 130 G€, is the second most important industry after the car manufacturing. The Italian food industry plants buy and transform 72% of domestic agricultural raw materials. Inevitably, the processes performed in food industries generate huge amounts of agro-industrial waste. For Italy, Petruccioli et al. (2011) reported productions of 2.4 Mt/y of grape pomace, 0.7 Mt/y of olive pomace and 0.2 Mt/y of both tomato pomace and soybean integuments. It can be estimated that the transformation of 1 t of agricultural raw materials generates from 30 to 100 kg of organic waste.

Agro-industrial waste, that includes both fruit and vegetable waste, may be stabilized by the anaerobic digestion (AD) process (Khalid et al., 2011). AD is known as a more environmentally friendly and energy saving process for stabilizing high-strength organic waste, than other disposal options like landfilling, incineration, and composting (Hosseini Koupaie et al., 2014; Traversi et al., 2013). In addition to biogas generation, AD benefits include enhancing nutrient characteristics of the dewatered digestate used as fertilizers as well as pathogens reduction. Greenhouse emissions are also decreased because the AD process diverts organic waste from landfills, thus preventing uncontrolled methane and carbon dioxide emissions from decomposition (Xie et al., 2011).

In spite of the potential advantages of the AD process for the management of agro-industrial waste, at present, in Italy, most of it is sent to composting plants. This work aims to carry out a technical and economic assessment of a more sustainable way of managing waste from food industry processes, by evaluating the convenience of producing heat and electricity in an on-purpose

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made anaerobic digester. The waste products considered in this work are generated in two food industry plants located in the NW Italy.

In order to proceed to the technical and economic assessment of the digester, the potential production of methane from the waste generated in the two plants was determined in both a semi-pilot (6-L, fed-batch mode) and pilot (300-L, semi-continuous mode) scale in mesophilic conditions. Values of the methane yield for waste originated from agro-industrial processes are reported in several studies (Dareioti and Kornaros, 2014; Garcia-Peña et al., 2011; Jiang et al., 2012; Yang et al., 2013). However, only a couple of very recent papers focus on tests carried out on fruit and vegetable waste fed as a single substrate to semi-continuous pilot scale reactors (Fiore et al., 2013; Scano et al., 2014).

In order to test the capacity of waste to produce methane in anaerobic conditions, different modes (batch, semi-continuous, continuous) and several scales (from lab to full scale) can be used. Traditional biochemical methane potential (BMP) tests have the undeniable advantage of taking up small volumes (usually from 100 mL to 1000 mL) and requiring very low efforts of personnel during test developments (Angelidaki et al., 2009; Cavaleiro et al., 2013; Lisboa and Lansing, 2013; Raposo et al., 2011; Triolo et al., 2012). However, the procedure does not assure reliable outcomes in the case of highly heterogeneous substrates and it is not suitable to highlight problems such as the irreversible acidification of the reactor (Kolbl et al., 2014).

In this work a first estimate of the methane production capacity of waste was obtained using fed-batch tests in a semi-pilot scale. The authors preferred fed-batch tests to traditional one-fed essays and employed larger vessels than usual (6 L instead of maximum 1–1.5 L) in order to test a substrate with high heterogeneity using a solid procedure. The fed-batch mode allowed the authors to feed higher amounts of substrate, guaranteeing the representativeness of the whole sample and avoiding possible inhibition in the methanogenesis phase due to the progressive acidification of the reactor. In addition, because of the effect of particle size and surface area of the substrate on the performance of the AD process (Novarino and Zanetti, 2012; Palmowski and Muller, 2000, 2003; Zhang and Banks, 2013), the larger volume allowed the authors to test highly heterogeneous substrates with realistic particle sizes.

The capacity of waste to produce methane obtained in the fed-batch mode was verified using a semi-continuous test carried out in the 300-L digester. The pilot scale test was necessary in order to obtain more reliable results on which to base the design of the full scale digester for the energy valorization of the waste products. The results of tests in the pilot scale are of particular interest especially for highly heterogeneous substrates. The outcomes of the experimentation were employed for a preliminary process and cost–benefit analysis of the full-scale AD digester for treating the waste produced in the two food industry plants.

2. Methods

2.1. Waste origin and characterization

Waste products considered in this work are generated in two food industry plants located in the NW Italy. The first plant (Plant 1) transforms and preserves several kinds of vegetables, mainly carrots, potatoes, onions, beetroots and celery with a capacity of 12,000 t/y. Processes carried out in Plant 1 generate around 350–400 t/y of organic waste. The organic waste from Plant 1 has a very high heterogeneity, because it comes from both the peeling process of vegetables and grating and cloth-filtering phases in the wastewater treatment plant (WWTP) contained within the food industry plant. The second food industry plant (Plant 2) specializes in the production of pesto sauce and other kinds of sauces with an end product capacity of 5000 t/y. Waste is made of residues of production and sub-standard products, the main components of which are basil and sunflower oil. The monthly amount of organic waste is approximately of 25–30 t. Plants with a production capacity similar to that of the plants studied, have electrical consumption in the order of 1000–1500 MWh/y and thermal consumption that ranges from $5 \cdot 10^2$ to 10^4 MWh/y, depending on the heat demand of the operations performed.

Two substrates coming from Plant 1 and Plant 2 were sampled, characterized and employed in the AD tests. The substrate from Plant 1 was a mixture of three waste products. The first waste product (named as "peeling") originated from the peeling process of vegetables. The second waste product (named as "screen") was separated from the grid screen positioned at the head of the WWTP contained within the food industry plant. The third waste product (named as "filtrate") was separated from the cloth filter positioned after the grid screen in the same WWTP. The produced amounts of the three waste products, on dry basis, were the same. For this reason the mix to employ for the tests was obtained by mixing identical amounts of each waste product (on dry basis).

The substrate from Plant 2 came from the production process of pesto sauce. According to the data supplied from the Plant, the principal components of this waste were basil and sunflower oil, in approximately the same amount. Minor components were cashew nuts, pine nuts and Parmesan cheese.

The physical and chemical characterization of substrates and the digestate, that resulted from the digestibility tests, included pH, total solid (TS) and volatile solid (VS) content, and elemental composition (C, H, N, S – this last analysis only for substrates). All parameters were determined according to standard methods (APHA, AWWA, WEF, 2005). The elemental analysis was performed by means of a CHNS–O Thermo Fisher Flash 2000 Analyzer EA 1112, assuming the oxygen content as the complementary fraction towards C, H, N, S contents. All the analyses were carried out in three replicates, on representative and significant amounts of the samples as in Roati et al. (2012). Determination of VS content and elemental composition were carried out on samples dried at 105 °C.

2.2. Semi-pilot scale test – fed-batch mode

Both substrates, that is the vegetable mix waste (VMW) and the waste from pesto sauce production (PSW, pesto sauce waste), were tested in a fed-batch mode. Tests were performed in mesophilic conditions (35 °C) in five replicates, using 6-L poly methyl methacrylate (PMMA) digesters placed in a thermostatic bath. The anaerobic environment was prepared by filling digesters with water, then replacing it with nitrogen. This procedure also ensures that the reactors were leak free. In order to simulate real digestion conditions, pH value was not adjusted and no nutrients were added. Each digester was manually mixed for 20–30 s once a day as in Ruffino et al. (2015).

The inoculums employed in the tests was prepared from 1000 mL of digestate collected from the anaerobic digesters of a municipal WWTP located in the same area of the two food industry plants. The inoculums was progressively fed with amounts of primary sludge, coming from the same WWTP, to reach a final volume of 3000 mL. The inoculums were considered ready when its daily biogas production was of less than 1% of the overall production recorded throughout the period of preparation.

For the test with the VMW, the inoculums had a TS content of 3.26 ± 0.31%, a VS/TS ratio of 64.3 ± 2.9% and a pH value of 7.23 ± 0.01 (average value on five replicates ± standard deviation). Each digester was fed with six aliquots of the substrate. Each aliquot contained 15 g of TS and was introduced into the digesters