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Energetic potential of the co-digestion of sludge with bio-waste in existing wastewater treatment plant digesters: A case study of an Italian province

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ABSTRACT

The effect of co-digesting sludge with bio-waste was investigated using an experimental apparatus set for reproducing the operating conditions of a full-scale digester in an existing wastewater treatment plant of 90,000 PE (population equivalent). An increase in the organic loading rate from 1.46 kgVS/m^3 day to 2.1 kgVS/m^3 day obtained by introducing 40 kg of biowaste per m^3 of sludge in the digester caused an increase in the specific methane generation from 90 NL/kgVS to 435 NL/kgVS. These results were used to assess the energetic potential of digesters in eight existing wastewater treatment plants operating in an Italian province with 28,000 PE to 90,000 PE. Results showed that these facilities were able to co-digest globally about 2900 tonnes per year of bio-waste and to generate about 3400 MWh/year of electricity.

1. Introduction

AD (anaerobic digestion) is a suitable method both for biodegradable waste treatment and renewable energy production, contributing to achieving the 2020 EU objective [1]. Concerning renewable energy production, waste materials like manure, crop residues, sewage sludge, algae, the OFMSW (organic fraction of municipal solid waste) and FVW (fruit and vegetable waste) are of particular importance since they do not compete with food crops [2,3]. Furthermore AD converts biodegradable substrates into two main streams: a biogas composed mainly of bio-methane and carbon dioxide and a quite stabilized soil improver for agricultural use [4]. Currently AD is widely used for the stabilization of WMS (waste-mixed sludge), *i.e.*, a mixture of primary sludge and waste-activated sludge, produced during wastewater pollutant removal in WWTP (wastewater treatment plants). About 36,000 WWTP operating in the EU have anaerobic facilities for sludge reactivity reduction [5]. About 10 million tonnes, on dry basis, of WMS are produced in the EU each year and its disposal amounts to about 50% of the total operating costs of WWTP [2]. Due to the low organic loadings from WMS, generally such AD facilities are oversized. This has given rise to the concept of co-digesting WMS with other biodegradable substrates [5]. For this aim, several substrates have been investigated, such as algae [6], bio-waste such as the organic waste arising from source-segregated collection and FVW arising from wholesale markets, food industries and households [7]. Tedesco et al. [6] reported that sludge acts better than other substrates for co-digestion with marine algae. Bolzonella et al. [5] reported that the co-digestion of waste-activated sludge and organic waste in a full-scale facility of 90,000 PE (population equivalent) led to an increase in biogas production from about 600 to 950 m^3 per day. Methane concentration ranged from about 66% v/v to about 68% v/v, whereas the OLR (organic loading rate) went from 1.02 kgVS/m^3 day to 1.21 kgVS/m^3 day. Gomez et al. [8] analyzed the effect of co-digesting a mixture of 22% primary sludge and 78% FVW. Results showed that for an OLR ranging from 0.8 kgVS/m^3 day to 3 kgVS/m^3 day, the specific biogas production ranged from 300 L/kgVS to 800 L/kgVS.

Environmental benefits arising from the AD of bio-waste have been extensively investigated in the literature. Bernstad and Jansen [9] found that for the Danish context, anaerobic digestion of bio-waste gave a higher net avoidance of greenhouse gas emission compared to incineration. These findings are in accordance with

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those obtained by Khoo et al. [10] and Sonesson et al. [11] concerning the AD of organic waste compared to incineration in Singapore and Uppsala (Sweden), respectively. On the contrary, a similar study performed by Di Maria and Micale [12] for an Italian waste management district gave opposite values, confirming the importance of taking the context into consideration in environmental analysis studies. Another important aspect of co-digestion is the possibility of processing bio-waste by AD with reduced investment and operating costs. Some of the main economic advantages are the possibility of using vessels already available in existing WWTP, together with managing the liquid fraction of the digestate *in situ*. In the present study, the operating conditions of an existing digester in a 90,000 PE WWTP were reproduced using a pilot-scale experimental apparatus. The energetic benefits generated by the co-digestion of sludge and bio-waste were analyzed at different OLRs. On the basis of these results, the amount of energy able to be generated by co-digesting sludge with bio-waste was evaluated in the existing digesters of WWTPs in an Italian province.

2. Material and methods

2.1. Sampling and characterization

The WMS was withdrawn from an existing WWTP of 90,000 PE (*i.e.* PV, Table 2) at the thickener outlet. The amount of sludge needed for running the pilot-scale apparatus for 1 week was stored at +4 °C. The remaining amount was frozen at −20 °C. FVW is usually generated in wholesale and/or retail markets, food industries and households. Its composition can vary depending on the season, and local and economic aspects. In analyzing the co-digestion of slaughterhouse waste, manure and FVW generated in La Paz (Bolivia) vegetable markets, Alvarez and Liden [13] reported about 30 different components, such as eggplant and cassava, with a percentage ranging from 0.5% w/w up to 14% w/w. Similarly the FVW used by Callagan et al. [14] for co-digestion with cattle slurry was made up of 9 components, such as potato and rice, with a concentration ranging from 3.9% w/w up to 24.5% w/w. In the present study the FVW was generated in the laboratory according to the composition proposed by Sosnowski et al. [15,16] (Table 1) concerning the co-digestion of FVW with sewage sludge. These components were blended to generate a homogenous material before being used in the co-digestion runs.

TS (total solids) (% w/w) and consequently MC (moisture content) (% w/w) were determined by measuring weight loss after heating at 105 °C for 24 h. VS (volatile solids) (%TS) were determined by measuring the change in weight of TS after burning at 550 °C for 24 h. The main chemical parameters were determined using a HACH Lange DR 3900 spectrophotometer. COD (chemical oxygen demand) (mgO_2/L), biological oxygen demand after 5 days (BOD_5) (mgO_2/L) and TVFA (total volatile fatty acids) (mg/L), expressed as acetate equivalent, were determined using LCK 014, LCK 555 and LCK 365 HACH Lange cuvettes, respectively. The same methodology was also used for total nitrogen (N_{tot}) and total phosphorous (P_{tot}) (mg/L) determination using LCK 238 and LCK 350 cuvettes, respectively. pH was determined with a kp 50 Delta Ohm probe.

Analyses were performed at least in triplicate both on the fresh substrates and on the digestate withdrawn from the pilot-scale apparatus.

Table 1
Food components (% by weight) used for bio-waste generation.

Component	%
Potato	55
Fruit and vegetables	28
Bread	5
Paper	2
Rice and pasta	10
Average moisture content	80

2.2. Pilot-scale apparatus and run procedure

The pilot-scale apparatus used in the analysis consisted of a 100-L gas tight anaerobic reactor [17,18] with a removable top (Fig. 1). The temperature was maintained at 35 °C ± 2 °C by the aid of a thermal heating jacket wrapping the digester and by a 2 cm thick insulated layer. The temperature was continuously monitored with a resistance temperature probe inserted inside the processed substrate. Stirring was continuously maintained by a temporized circulating pump withdrawing a given rate of liquid from the reactor top and injecting it at the reactor bottom. Gas produced during the process was continuously withdrawn from the reactor top, piped first to the dehumidification system and then to the thermal gas flow meter (±0.1 FS). Gas composition was determined with infrared sensors for CH_4 and CO_2 concentrations (% v/v) (±1%) and with electrochemical cells for O_2 and H_2S (% v/v) (±2%). A volumetric pump was used for feeding the reactor, whereas the valve positioned at the reactor bottom was used to withdraw the digestate. Operating conditions similar to the full-scale digester of one of the existing plants (PV, Table 2) in the province of Perugia were reproduced: Temperature = 35 °C ± 2 °C; TS = 4%; HRT (hydraulic retention time) = 14 days, which corresponds to that of sludge retention. Hence about 7 L/day of WMS were fed into the pilot-scale apparatus. Runs were started by introducing 100 L of digestate withdrawn from the full-scale facility into the pilot digester. The OLR was increased by adding 0.7 L, 1.4 L, 2.1 L and 2.8 L of FVW with a TS concentration of 4% w/w, eventually adjusted with demineralized water, to the daily feed, which further decreased the HRT. This corresponded, respectively, to the following OLRs: 1.7 $kgVS/m^3$ day; 2.1 $kgVS/m^3$ day; 2.46 $kgVS/m^3$ day; 2.8 $kgVS/m^3$ day.

An adaptation period ≥ 3HRT was imposed for each new OLR. The new OLR was then maintained for at least two successive weeks. The process chemical and physical parameters along with the biogas production and composition reported in the present study refer to this second phase.

2.3. Mathematical correlations and main assumptions

Experimental runs were also analyzed using mathematical models to evaluate the following parameters:

1) VS removal (%), given by the ratio between the amount of VS reduced by the pilot digester and the VS at the digester inlet, Eq. (1);
2) The MPR (methane production rate) ($NLCH_4/m^3$ day), which is the amount of methane generated daily per unit volume of the digester;
3) The SMP (specific methane production) ($NLCH_4/kgVS$), which is the amount of methane generated per kg of VS fed to the digester;
4) The net electrical efficiency (η_{el}) (%) of the co-generator used for energy recovery from the biogas, Eq. (2). This equation correlates, on a statistical basis, the electrical power output (kW_e) of industrial co-generators to their η_{el} as reported by Walla and Schneeberger [19].