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Energetic and environmental sustainability of the co-digestion of sludge with bio-waste in a life cycle perspective

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HIGHLIGHTS

- Co-digestion of sludge and bio-waste in existing WWTP digester for energetic and environmental benefits.
- Increase in methane yield from 90 NL/kg VS to 435 NL/kg VS.
- Maximum environmental benefits depending on the amount of energy recovered.
- Uncertainty analysis confirmed the environmental benefits for a wide range of possible values.

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ABSTRACT

The integrated management of sludge and bio-waste by co-digestion and composting were investigated in a life cycle perspective. The working operations of a full-scale digester of an existing wastewater treatment plant for waste-mixed sludge (WMS) stabilization were reproduced using a pilot-scale apparatus. The effect of WMS co-digested with fruit and vegetable waste (FVW) was investigated at different organic loading rates (OLR), from 1.46 kg VS/m^3 day to 2.8 kg VS/m^3 day, and at reduced hydraulic retention time, from 14 days to about 10 days. Methane production per unit of digester volume increased from about 140 NL/m^3 day to a maximum of about 900 NL/m^3 day when OLR was increased from 1.46 kg VS/m^3 day to 2.1 kg VS/m^3 day. The maximum electrical energy producible from the full-scale anaerobic facility was about 3,500,000 kW h/year. In these conditions the electrical power output and the net efficiency of the co-generator were 470 kW and 37%, respectively. The life cycle analysis study highlighted the benefits achievable in terms of avoided resource depletion and ozone depletion potential. The best environmental performances were for an ORL of 2.1 kg VS/m^3 day.

1. Introduction

Aerobic and anaerobic biological processes are widely exploited for the management of bio-waste and sludge. In general aerobic processes such as composting are of particular interest because of their robustness and ability to return stabilized materials exploitable as soil improvers even if energetic consumption is high [1]. On the other hand, investment costs are higher for anaerobic digestion (AD) [2], but biodegradable substrates can be converted into two main streams: a biogas composed mainly of methane and carbon dioxide exploitable as fuel for renewable energy production; a quite stabilized soil improver for agricultural use [3]. Furthermore AD is also an important process for achieving the 2020 EU objectives [4] on greenhouse gas (GHG) reduction and renewable energy production. Concerning renewable energy production, waste materials like manure, crop residues, sewage sludge, the organic fraction of municipal solid waste (OFMSW) and fruit and vegetable waste (FVW) are of particular interest since they do not compete with food crops as substrates for AD [5]. Currently AD is widely used for the stabilization of waste-mixed sludge (WMS), a mixture of primary sludge and waste-activated sludge, produced during wastewater pollutant removal in wastewater treatment plants (WWTP). About 36,000 WWTP operating in the EU have anaerobic facilities for sludge reactivity reduction [6]. WMS production in the EU is about 10 million tonnes per year, on dry basis, and its disposal amounts to about 50% of the total operating costs of WWTP [5]. Due to the low organic loadings of WMS originating from WWTP, such AD facilities are generally oversized. This has given rise to the concept of co-digesting WMS with other biodegradable substrates [6] for increasing the energetic efficiency of these facilities. The substrates most investigated have been the OFMSW

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arising from source-segregated collection and fruit and vegetable waste (FVW) arising from wholesale markets [7,8]. Bolzonella et al. [6] reported that the co-digestion of waste-activated sludge and OFMSW in a full-scale facility of 90,000 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 68% v/v, whereas the organic loading rate (OLR) of the existing digester went from 1.02 kg VS/m^3 day to 1.21 kg VS/m^3 day. Gomez et al. [9] analyzed the effect of co-digestion of a mixture of 22% primary sludge and 78% FVW. Results showed that for an OLR ranging from 0.8 kg VS/m^3 day to 3 kg VS/m^3 day, the specific biogas production ranged from 300 L/kg VS to 800 L/kg VS. Cavinato et al. [10], Di Maria et al. [11], and Abdullai et al. [12] found that WMS and biowaste co-digestion also affected digestate quality for possible agronomic use. In analyzing the co-digestion of primary sludge and FVW, Gomez et al. [13] highlighted the effect of mixing conditions and OLR on biogas yield. Results showed that about 800 L/kg VS removed were generated during low intensity mixing at OLR = 2.5 kg VS/m^3 day. Similar performances were also reported by [14,15] for co-digestion, even if biogas yields were lower. The filterability of sludges after co-digestion was investigated by [16], showing that the best process performances were achieved at a FVW-to-sludge ratio of 30:70. Several studies were also conducted on the effects that FVW co-digestion can have on the anaerobic microbial guilds [17–19]. There was a high correlation between the amount of FVW co-digested, digester performances and microbial populations.

Also environmental benefits arising from the adoption of AD have been extensively reported in the literature. Bernstad and La Cour Jansen [20] found that for the Danish context anaerobic digestion of OFMSW gave a higher net avoidance of GHG compared to incineration. These findings are in accordance with those of [21,22] concerning the AD of OFMSW compared to incineration in Singapore and Uppsala (Sweden), respectively. On the contrary, a similar study performed by [23] for an Italian waste management district gave opposite values, confirming the importance of taking the energetic context into consideration in environmental analysis studies. The environmental aspects concerning the co-digestion of WMS with bio-waste has been less investigated. Liu et al. [24] analyzed the impact of co-digestion of sludge and FVW, but the investigation was limited only to GHG emissions. Krupp et al. [25] compared OFMSW co-digestion with WMS with mono digestion and composting. Also in this case the environmental analysis was limited only to the gaseous emissions affecting global warming, terrestrial eutrophication, aquatic eutrophication and ecological toxicity. Other impacts concerning the quality and possible agronomic use of the digestate were disregarded. In a life cycle assessment (LCA) perspective [26] compared different management options for sludge and food waste for a given Italian district. Results indicated that the most environmentally sound option was co-digestion followed by composting of the solid digestate. Effects on system performances, digestate quality and consequent environmental impacts due to changes in digester operating conditions such as OLR and hydraulic retention time (HRT) were not investigated. Hence, energetic and environmental benefits achievable by WMS co-digestion with bio-waste is worthy of further investigation. In the present study the integrated management of WMS and FVW was investigated. Integrated management was based on the simultaneous exploitation of co-digestion and composting. Composting was used for the FVW not co-digested. The operating conditions of a full-scale digester were reproduced using an experimental apparatus. On the basis of the experimental data both energetic and environmental analyses were performed.

2. Material and methods

2.1. Sampling and characterization

The WMS was withdrawn at the thickener outlet of an existing WWTP of 90,000 population equivalent, operated at a high retention time for the activated sludge (*i.e.* 2 week), for reducing both the amount of waste sludge generated and its biological reactivity. The amount of sludge necessary 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 produced in wholesale markets and generally contains impurities such as plastics, metals and other inert materials. As in full-scale facilities [27] these impurities can damage some components of the pilot-scale apparatus (Fig. 1) and the lab-equipment used for sample conditioning such as grinders and mixers. Since it is very difficult to completely remove these materials, the FVW was made in the laboratory according to [28,29] by blending the materials indicated in Table 1.

TS (% w/w) and consequently moisture content (MC) (% w/w) were determined by measuring weight loss after heating at 105 °C for 24 h. VS (% TS) was determined by measuring the change

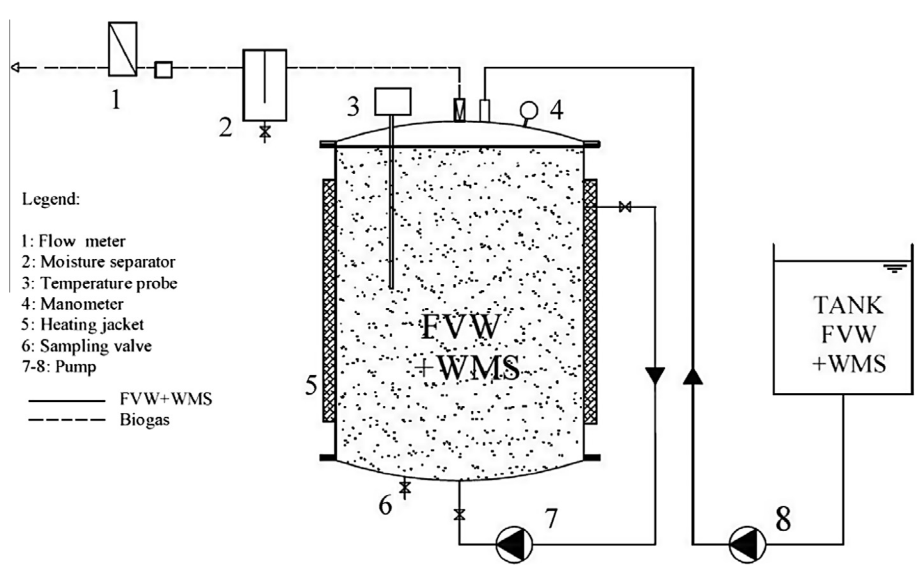

Fig. 1. Pilot apparatus scheme.