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The contribution to energy production of the aerobic bioconversion of organic waste by an organic Rankine cycle in an integrated anaerobic–aerobic facility

Francesco Di Maria*, Caterina Micale

Dipartimento di Ingengeria, Università di Perugia, Via G Duranti 67, 06125 Perugia, Italy

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ABSTRACT

An integrated anaerobic digestion (AD) and aerobic bioconversion facility, equipped with an organic Rankine cycle (ORC), was analyzed for the management and recovery of energy from organic waste (OW). The ORC was fuelled mainly by the exhaust heat ejected at about 340 K by the aerobic treatment of OW eventually supplemented with the heat generable by the combustion of a given fraction of the biogas generated by AD. For an integrated facility processing 25,000 tonnes/year of OW, the net electrical output of the internal combustion engine fuelled by the biogas was about 1090 kW. If fuelled only with the exhaust heat from the aerobic treatment, the ORC can generate up to 18 kW, leading to a global system efficiency increase of about 2%. For a compression ratio ≤2, exploitation of the biogas generated by AD for increasing the amount of heat and temperature at the ORC inlet up to about 350 K leads to further energetic benefits. A preliminary economic analysis indicates an operational expenditure of about 38 €/MWh for the proposed solution.

1. Introduction

Biological treatments are widely exploited for managing and processing OW, for both energy production and biological reactivity reduction [1–7]. Depending on the features of the OW, AD can lead to the production of about 80–210 Nm^3 of biogas per tonne of OW, with a CH_4 concentration ranging from 50 to 70% v/v [8–14]. The economic viability of AD [11–15] requires a minimum amount of about 20,000 tonnes/year of OW. Biochemical transformation of the OW during AD results in a digestate characterized by rather high residual biological reactivity and phytotoxicity, requiring a successive aerobic treatment to obtain the features suitable for disposal [16–18] or recovery (*i.e.* organic fertilizer) [19–23]. For these reasons AD facilities used for OW are usually integrated with a successive aerobic treatment section [12]. In the aerobic process, bacteria oxidize the OM [24], exploiting the air supplied by electric fans, and generate about 17,000–18,000 kJ/kg OM [25] of heat. This leads to an increase of the temperature of the OW and consequently of exhaust air up to 75 °C [26,27]. Furthermore the exhaust air ejected by the process has a relative humidity close to 100%. Di Maria et al. [27] evaluated the possibility of using heat pumps to recover this heat for civil use. The daily amount of heat recoverable ranged from about 120 to 350 kWh/tonne OW. Another possible solution for recovering this large amount of low-grade heat could be by ORC systems. The ORC is made up of the same components as a conventional steam power plant, but uses an organic fluid to extract low-grade thermal energy to generate electricity. ORC is commonly used in industrial applications such as biomass power [28], solar power [29], geothermal power [30,31] and waste heat recovery power [32]. Bidini et al. [33] analyzed the use of ORC in an integrated gas turbine-geothermal power plant for recovering low-grade heat ejected from the gas turbine exhaust after geothermal fluid heating. Wang et al. [34] analyzed the effect of different working fluids on ORC efficiency for engine waste heat recovery. Similarly Hung et al. [35] investigated the effect of different organic working fluids on ORC efficiency using heat generated by solar ponds and ocean thermal energy. Other authors [36–41] have reported studies concerning low-grade heat recovery by micro-ORC systems with a power output of about 500 W with quite high levels of efficiency. The exploitation of the heat ejected by internal combustion engines has already been investigated. However, there is a lack of information on the possibility and benefits of exploiting ORC for energy recovery from the heat generated during the

* Corresponding author. Tel.: +39 0755853736; fax: +39 075 5853703.
E-mail address: francesco.dimaria@unipg.it (F. Di Maria).

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aerobic bioconversion of the OW digestate. Considering that the amount OW produced in the EU27 is about 100,000,000 tonnes/year [42], this solution could be interesting both for renewable energy generation and for improving the energy efficiency of OW treatment facilities.

2. System modeling

2.1. AD of OW

AD technologies can be grouped into three main categories on the basis of moisture content: Wet AD with $H > 85\%$; Dry AD with $75\% < H < 85\%$; SADB with $65\% < H < 75\%$.

The higher the moisture content required by the technology, the greater is the number of pretreatments necessary for processing the OW (*e.g.* shredding, screening, diluting, pulping, settling). Furthermore, the digestate discharged from the wet and dry digesters is not suitable for a successive direct aerobic treatment due to its high moisture content. Even though there is a lower amount of biogas generated [11,12], the SADB requires very few pretreatments and the resulting digestate has features suitable for being processed directly in an aerobic treatment facility. For these reasons the following analysis was based on an integrated anaerobic/aerobic treatment of the OW based on SADB. In full-scale SADB, the digesters consist of a suitable number of gastight, static and batch anaerobic biocells (Fig. 1), operating in parallel at mesophilic conditions (*i.e.* +35 °C). Generally the OW is processed for about 4 weeks after which the digestate is moved to the aerobic section. Loading, unloading and handling of the OW and digestate are performed by wheeled loaders. In each anaerobic biocell, the main process parameters such as T and H can be controlled. The energetic potential of SADB was investigated using an experimental apparatus (Fig. 2) mainly consisting of a 100-L anaerobic, batch static reactor. T was kept under mesophilic conditions (35 °C ± 2°) using a thermal band, powered by a potentiometer, fitted with an RTD. The biogas was extracted from the reactor top, treated in a moisture separator vessel and piped to a gas flow meter. The biogas composition by volume was analyzed with infrared analyzers for

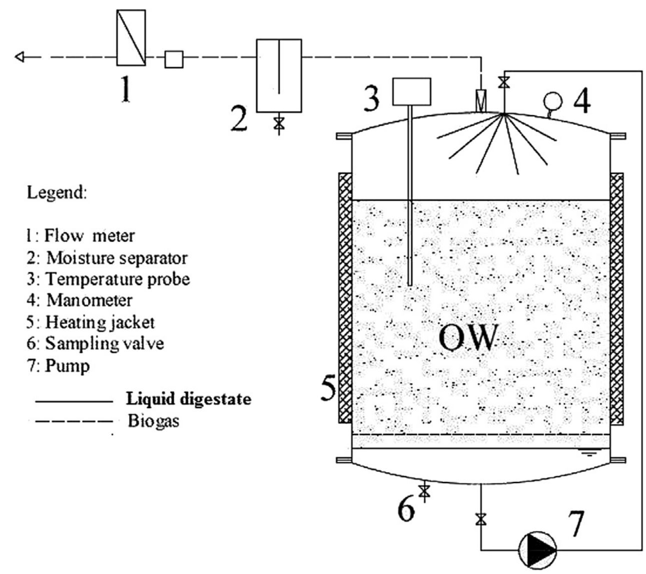

Fig. 2. Solid Anaerobic Digestion Batch (SADB) experimental apparatus.

CH_4 (±1%) and CO_2 (±1%), and with electrochemical cells for O_2 (±2%) and H_2S (±2%). Due to their low concentration, other biogas components (*i.e.* NH_3, CO, H_2, mercaptan, hydrocarbons) were not analyzed further in this study. Before and after each run, the TS and consequently H of the OW and of the digestate were evaluated by drying at 105 °C for 24 h. The VS were evaluated by heating the TS at 550 °C for 24 h. Three different runs were performed.

2.2. ICE

The biogas generated during AD was used for fueling a spark ignition ICE for the generation of electrical energy. Electrical efficiency and power of the ICE was determined on the basis of the study of Walla and Schneeberder [15] analyzing 65 different ICE for

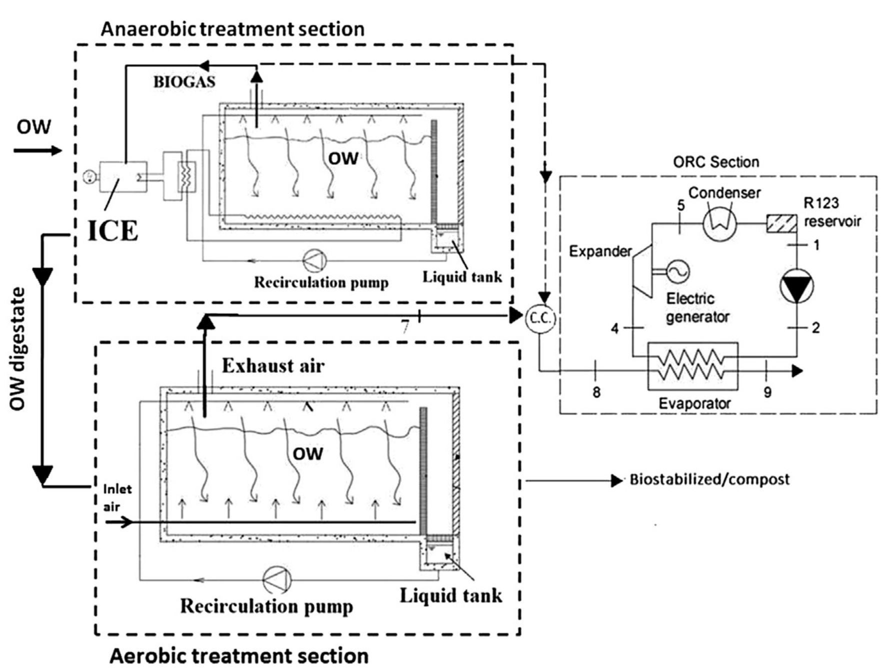

Fig. 1. Scheme of the proposed anaerobic/aerobic OW treatment system with organic Rankine cycle (ORC).