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Electrical energy production from the integrated aerobic-anaerobic treatment of organic waste by ORC

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A B S T R A C T

The energetic performance of an ORC system fueled by the heat generated from the integrated aerobic/anaerobic treatment of organic waste was analyzed. The temperature and heat content of the exhaust air arising from the aerobic treatment were increased by the combustion of the biogas produced by the anaerobic digestion of a fraction of the same waste. On the basis of the amount of excess air exploited in the process, for each tonne of organic waste treated, it was possible to produce from 30 to 90 kg of exhaust air per day with a mean temperature ranging from 330 to 340 K. By processing from 0.5% to 16% of the whole organic waste in an anaerobic digestion section instead of the aerobic one, it was possible to increase the exhaust air temperature from 340 to 510 K, leading to an increase in the ORC size from about 0.05 to about 1 W/tonne/year. The best energetic utilization of the biogas was achieved for ORC compression ratios from 1.5 to 2 and for maximum air temperatures from 335 to 340 K. In these conditions, by using a micro-ORC system (*i.e.* <15 kW), it was possible to convert about 20% of the energy content of the biogas into electrical energy.

1. Introduction

Anaerobic and aerobic biological treatments are widely exploited in processing organic waste (OW) both for energy production and for biological reactivity reduction before final recovery and/or disposal [1–7]. In particular anaerobic digestion (AD) can lead to the production from about 80 Nm^3 up to 210 Nm^3 of biogas per tonne of processed OW. The methane concentration usually ranges from 50 to 70% v/v [8–14], whereas the other main component is CO_2. The corresponding lower heating value (LHV) varies from 18,000 kJ/Nm^3 to 24,000 kJ/Nm^3 and biogas can be exploited as fuel in internal combustion engines for renewable energy production.

The viability of AD is greatly influenced by plant size and by the variation in the rate and composition of OW during the year [11,12,15]. Aerobic treatments are used to reduce both OW and AD digestate residual biological reactivity before disposal or for the production of organic fertilizer, depending on OW quality [16]. As extensively demonstrated [17–19], aerobic treatment can lead to long-term emission reduction in landfills, up to 90%. If OW quality is compatible with the characteristics of organic fertilizer [20–22], aerobic bioconversion is generally used to convert the OW to substances exploitable for agricultural use. During the aerobic process, bacteria oxidize the organic matter [23], generating about 17,000–18,000 kJ/kg OM [24] of heat. Due to the high initial concentration of OM, heat release is particularly high in the first 2–4 weeks, causing an increase in the OW mass and consequently in process air temperatures. Maximum temperatures achieved in full-scale facilities range from 55 °C to 75 °C, depending mainly on thermal loss, OW moisture content OM content and process air rate [25,26]. In a previous study, Di Maria et al. [26] evaluated the possibility of recovering this heat for civil use by heat pumps. Results showed that the process exhaust air temperature ranged from about 55 °C to 70 °C and the amount of heat ejected daily ranged from about 120 to about 350 kWh/tonne depending mainly on the amount of OW treated and the process air rate.

Another possible solution for recovering this amount of low temperature heat is by using the organic Rankine cycle (ORC) system. The ORC uses 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 practical industrial applications such as biomass power [27,28] solar power [29] also aimed at water production [30], ocean thermal energy conversion, geothermal power [31,32], and waste heat recovery power [33]. Bidini et al. [34] analyzed the exploitation of ORC in an integrated gas turbine-geothermal power plant for recovering low-grade heat ejected from gas turbine exhaust after geothermal fluid heating. Gewald et al. [35] showed that ORC can improve the efficiency of landfill gas-fired power plants by about 12%. Desideri and

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Di Maria [36] reported that the exploitation of ORC for recovering exhaust heat from a humid air turbine system can lead to an overall cycle efficiency increase from 1.6 to 2.2%. Wang et al. [37] analyzed the effect of different working fluids on ORC efficiency for engine waste heat recovery. Similarly Hung et al. [38] investigated the effect of different organic working fluids on ORC efficiency using heat generated by solar pond and ocean thermal energy. ORC is a promising solution for decentralized, small- (*i.e.* <100 kW) and micro- (*i.e.* <15 kW) scale combined heat and power generation [39–41] and for this reason it is particularly used in biomass-fired plants. Even if its efficiency is low, between 6% and 17%, ORC has low maintenance and personnel costs [41]. Dong et al. [42] reported that costs are comparable with gasification in the same small- and micro-scale range. Furthermore, among the small number of commercially viable biomass gasification systems, only a few have been shown to be economical [39]. On the contrary, several small-scale ORC systems are operating and their viability has been fully proven [39–41]. Anyway there is a lack of investigation about the possibility of exploiting ORC for electrical energy production from the heat produced during the bioconversion of OW. Considering the large amount OW produced yearly in the UE27, about 100,000,000 tonnes [42] the efficiency of an ORC using the heat generated by integrated aerobic/anaerobic bioconversion of OW was theoretically investigated. System performances were also investigated using specific figures of merit.

2. Material and methods

2.1. Aerobic treatment model

One of the most widespread technologies for the first 2–4 weeks of OW aerobic treatment is the use of several concrete biocells (Fig. 1) operating in parallel and in batch mode. Full-scale biocells have a mean width and height of about 5 m and a length generally more than 15 m, depending on the amount of waste to be processed. Once loaded, usually by a wheeled loader, the cell is closed by a specially designed door to avoid air leakage. Electric fans supply the air through perforated floor to pass equally through the OW heap. Exhaust air, with an increased temperature, is then collected from the biocell roof before being discharged. The main process parameters such as temperature (T), humidity (H) and air rate are usually monitored and controlled inside the biocells. Once a large fraction of the initial rapidly biodegradable OM content has been oxidized, causing a drop in heat generation and OW temperature, the further aerobic treatment is usually carried out by arranging the material in an open heap. The emptied biocell can then be loaded with fresh OW for a new cycle. In any case the largest amount of heat is generated around the 5th to the 20th day of treatment and can contribute significantly to the heat for feeding the ORC. OW is composed of several biodegradable substrates such as fruit waste, meat waste, paper and yard waste, even if traces of impurities may also be present. From the results of a study performed for an Italian situation [12], the amount of impurities, like plastics and metals in OW coming from high-quality source segregation was <6% w/w. The other fraction >94% w/w was biodegradable materials. The elemental composition of the OM has been investigated by several authors [23,24] who showed that the principal elements are C, H, O and N. According to these results, the average composition of the OM qA is defined by (Eq. (1)).

$$C_6H_{10}O_4 \tag{1}$$

The stoichiometry of the aerobic process is shown in Eq. (2), where the OM is oxidized generating mainly carbon dioxide, water and heat.

$$(C_6H_{10}O_4)_x + 6.5O_2 = (C_6H_{10}O_4)_{x-1} + 6CO_2 + 5H_2O + 2578.6\ \text{kJ} \tag{2}$$

On the basis of Eq. (2), it is possible to quantify the λ coefficient Eq. (3) defined as the ratio between the effective ($\dot{m}_e$) and stoichiometric ($\dot{m}_s$) mass air rate (kg/s) supplied during the process. To

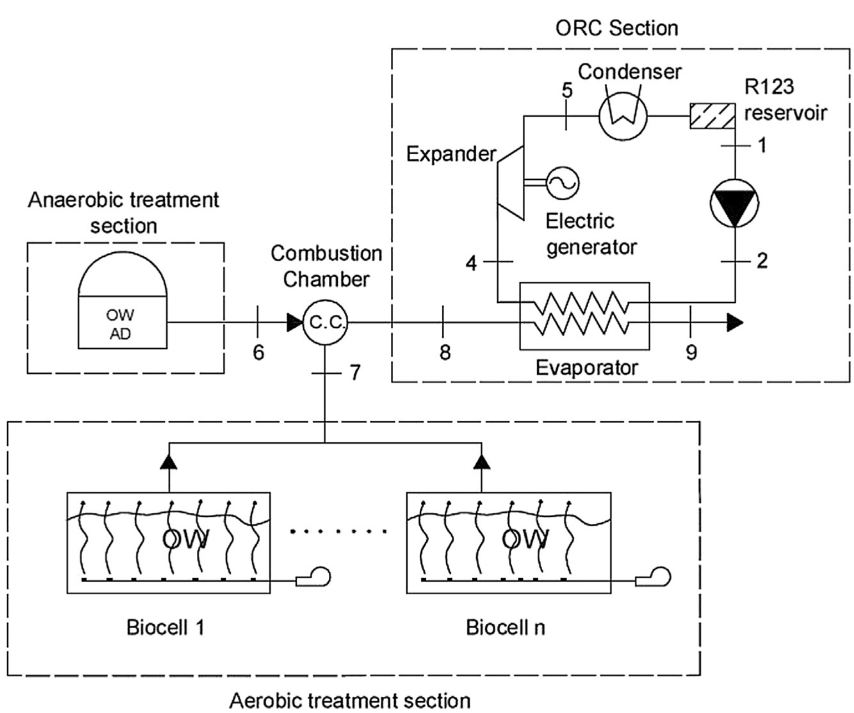

Fig. 1. Scheme of the integrated aerobic-anaerobic system with organic Rankine cycle (ORC).