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Biogas from anaerobic digestion of fruit and vegetable wastes: Experimental results on pilot-scale and preliminary performance evaluation of a full-scale power plant

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ABSTRACT

This paper presents the experimental results obtained through an anaerobic digestion pilot plant by using fruit and vegetable wastes as single substrate. The substrate materials were sampled from the wastes produced by the Fruit and Vegetable Wholesale Market of Sardinia (Italy).

The experimental study was carried out over a period of about 6 months to evaluate the most suitable operating parameters of the process depending on the availability of different kinds of fruit and vegetable wastes over the different periods of the year. Overall, the optimum daily loading rate of wastes was 35 kg/d, with a corresponding hydraulic residence time of 27 days. The optimum organic loading rate ranged from 2.5 to 3.0 kg_{VS}/m^3 d and the average specific biogas production was about 0.78 Nm^3/kg_{VS}, with a specific methane yield of about 0.43 Nm^3/kg_{VS}.

The results of the experimental investigation were used for a preliminary performance evaluation of a full-scale anaerobic digestion power plant for treating all the fruit and vegetable wastes produced by the Wholesale Market of Sardinia (9 t/d). The estimate of daily methane production (290 Nm^3/d) leads to a CHP unit with a power output of about 42 kW and an annual electrical production of about 300 MW h/year (about 25% of the wholesale market electrical consumption). The AD power plant also shows interesting economic features, since its energy production cost (about 150 €/MW h) is slightly lower than the energy purchase cost of the wholesale market (about 200 €/MW h) and a Pay-Back Time of about 7.25 years can be achieved in the case of dispatching the electrical energy to the national grid. The PBT decreases to about 5.4 years if 50% of the available thermal energy is used to substitute heat production from fossil fuel boilers.

1. Introduction

Anaerobic digestion (AD) is a biochemical degradation process that is widely used for the treatment and energy recovery from many kinds of biomass, especially agricultural products and agro-industrial wastes [1–5]. The spread of this technology during the last decades is in accordance with the environmental and sustainability policies adopted by European Member States and with the increasing use of low-cost feedstock in energy production from renewable sources.

The main product of the anaerobic digestion process is a gas mixture (biogas) mainly composed of methane (CH_4) and carbon dioxide (CO_2) that is used as fuel for power and heat production. A secondary product of the process is a sludge residue (digestate) that can be directly used as soil amendment [6,7] or as starting material for high quality compost preparation [8–10]. Since the digestate contains significant amounts of unconverted organic matter, it could be used as fuel for energy production after a drying treatment.

Fruit and vegetable wastes (FVWs) are a very important class of residues because they are produced in very large amounts in all the wholesale markets and in other activities in the world and their landfill disposal is quite difficult due to their very high perishability [11,12].

Fruits and vegetables are quickly degraded by contaminating microorganisms and this takes place even faster when they exhibit signs of mechanical damage or are excessively ripe. This generates high environmental complications even for short-term disposal. Moreover, the production of FVWs increases the operating costs of the markets due to both sales losses and transport and disposal costs.

Scientific literature contains several studies on anaerobic digestion of FVWs [6,13–18]. However, just in a few studies have the

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Nomenclature

C_p	specific heat (J/kg K)
$C_{O\&M}$	operation and maintenance cost (€)
C_T	total annual costs (€)
E_{AUX}	auxiliary consumption energy (kW h)
E_N	net energy production (kW h)
h	specific enthalpy (J/kg)
H	utilization factor (–)
m	mass (kg)
P_M	mechanical power (W)
Q_F	substrate feeding heat (J)
Q_H	reactor electrical heat (J)
Q_L	reactor heat losses (J)
Q_R	biochemical reaction heat (J)
S	reactor outer surface (m^2)
t	time (s)
T_A	ambient temperature (°C)
T_R	reactor temperature (°C)
U	overall heat transfer coefficient (W/m^2 K)
η_M	mechanical efficiency (–)

Subscripts

B	biogas
D	digestate
F	feedstock

Acronyms

AD	anaerobic digestion
CCR	Capital Charge Rate
CHP	Combined Heat and Power
CoE	Cost of Energy
FOS/TAC	ratio of volatile organic acid to alkaline buffer capacity
FVWs	fruit and vegetable wastes
GPR	Gas Production Rate
HHV	Higher Heating Value
HRT	Hydraulic Residence Time
LHV	Lower Heating Value
OLR	Organic Loading Rate
TCI	Total Capital Investment
TS	Total Solid
VS	Volatile Solid

results been obtained using FVWs as single substrate and, to the authors' knowledge, most of these experiments were performed in laboratory scale reactors (maximum size around 20 l). The only experiments performed on pilot and industrial scale reactors used fruit and vegetable wastes in co-digestion with other materials [19–21].

The aforementioned literature shows that anaerobic digestion of FVWs without any co-substrate is a challenging task because their high simple sugars content often promotes fast acidification of the biomass with a resulting inhibition of methanogenic bacteria activity. To reduce the effect of acidification and bacteria inhibition processes, other substrates are often added for co-digestion (such as manure and sewage sludge). In fact, the addition of suitable substrates ensures a better process stability by keeping almost constant the volatile solids content and by avoiding the increase of easily degradable substances. Unfortunately, most of the time it is very difficult to guarantee the availability of suitable amounts of other kinds of substrates for co-digestion of FVWs.

A better solution to reduce the effects of the acidification process is to feed the reactor with well-balanced mixtures of fruit and vegetable wastes to reduce the amount of fruit with high simple sugars content. Moreover, the adoption of a two-stage AD reactor allows to improve the process stability, even though it requires more complex and expensive treatment plants [22,23].

Proper design of a full-scale FVWs treatment plant requires an extensive knowledge of the entire AD process and in particular of the effects produced by the chemical composition of the substrate both on the biogas production rate and the overall energy balance of the system. For this reason, the main experimental results of a pilot-scale anaerobic digestion reactor (1.13 m^3 of volume) fed by FVWs single substrates are presented in this paper. In particular, the substrate materials were sampled from the wastes of the Fruit and Vegetable Wholesale Market of Sardinia (Mercato Ortofrutticolo della Sardegna – Italy). This market, the largest of the island, receives around 150,000 t/year of fruit and vegetables and produces 8–10 t/d of wastes. The experiment was carried out over a period of about 6 months to assess the effects produced by the availability of different kinds of fruit and vegetable wastes over the different periods of the year and to find the optimum operating parameters of the process. The results of the experimental investigation were then used for a preliminary performance evaluation of a full-scale anaerobic digestion power plant for treating all the FVWs produced by the Wholesale Market of Sardinia.

2. Materials and methods

2.1. Pilot-scale anaerobic digestion system

Fig. 1 shows the pilot scale anaerobic digestion plant used for the experimental investigation. The plant is equipped as follows: a cutter for substrate pre-treatment, a feeding hopper, a tubular horizontal reactor, a pneumatic feeding pump, a pneumatic digestate discharge pump, a biogas measuring and treatment unit, a digestate storage tank, an air compression unit, a gas holder and a control and supervision system. As shown in Fig. 1, the main pieces of equipment of the process are allocated inside a container.

After cutting, the biomass is delivered to the feeding hopper, where it is mixed by means of a vertical stirrer before being pumped inside the reactor. The feeding hopper is mounted on load cells, it is thermally insulated and can be heated through an electric heater. The tubular horizontal reactor has an overall volume of 1.13 m^3, it is partially insulated with a polymeric layer and equipped with a radial stirrer and an electrical heating system which guarantees an operating temperature up to 60 °C. The temperature is automatically monitored and regulated by means of three resistance temperature sensors (Pt 100) placed along the reactor and connected to the heating system. Reactor internal pressure is measured by means of a pressure transducer.

The biogas collection system includes a condensation trap for moisture removal, a flow meter and a polymeric gas holder. The digestate is removed from the reactor through a pneumatic discharge pump and conveyed to the digestate tank placed on load cells. Table 1 reports the technical specifications of the main pieces of equipment.

The pilot plant is controlled by a PLC system that receives signals from the different sensors and drives the main electrical and pneumatic pieces of equipment (pumps, stirrers, heaters, etc.). The following parameters are continuously measured, controlled and recorded by the PLC system: mass of feeding biomass and digestate, volume of produced biogas, temperature along the reactor