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Enhanced mesophilic anaerobic digestion of food waste by thermal pretreatment: Substrate versus digestate heating

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ABSTRACT

Food waste (FW) represents a source of high potential renewable energy if properly treated with anaerobic digestion (AD). Pretreating the substrates could yield a higher biomethane production in a shorter time. In this study, the effects of thermal (heating the FW in a separate chamber) and thermophilic (heating the full reactor content containing both FW and inoculum) pretreatments at 50, 60, 70 and 80 °C prior to mesophilic AD were studied through a series of batch experiments. Pretreatments at a lower temperature (50 °C) and a shorter time (<12 h) had a positive effect on the AD process. The highest enhancement of the biomethane production with an increase by 44–46% was achieved with a thermophilic pretreatment at 50 °C for 6–12 h or a thermal pretreatment at 80 °C for 1.5 h. Thermophilic pretreatments at higher temperatures (>55 °C) and longer operating times (>12 h) yielded higher soluble chemical oxygen demand (CODs), but had a negative effect on the methanogenic activity. The thermal pretreatments at the same conditions resulted in a lower solubilization of COD. Based on net energy calculations, the enhanced biomethane production is sufficient to heat up the FW for the thermal, but not for the thermophilic pretreatment.

1. Introduction

Food waste (FW) is a mixture of organic materials derived from the processing, sorting, preparation, cooking and handling of food. On a global scale, the most common FW stabilization technology at present is still landfilling followed by biological, thermal and thermochemical conversation technologies. Landfills are strongly discouraged by legislations such as the EU Directive on Landfills (1999/31/EC) and the Waste Framework Directive (2008/98/EC), as they contribute to environmental impacts including soil and groundwater pollution, greenhouse gas (GHG) emissions and utilization of huge land areas (Grosso et al., 2010; Holm-Nielsen et al., 2009). Due to the high moisture content and easily biodegradable characteristics of FW, biological treatments (anaerobic or aerobic) are preferred over thermal or thermochemical conversation technologies. Although aerobic treatment like composting provides a promising alternative to landfill disposal, anaerobic digestion (AD) is more favourable due to the following advantages: (i) production of renewable energy; (ii) less land and space required; (iii) more controlled emissions of GHG and toxic gases such as ketones and aldehydes; (iv) digestate can be used as soil conditioner or fertilizer; and (v) pathogen proliferation is prevented (Ariunbaatar et al., 2014a; Guo et al., 2014; Kastner et al., 2012; Mata-Alvarez et al., 2000; Zhang et al., 2009).

The AD process is mainly operated at mesophilic (30–40 °C) or thermophilic (45–60 °C) conditions. Theoretically, thermophilic AD (TherAD) is preferred over mesophilic AD (MesAD), as recent studies have shown that: (i) TherAD is kinetically favoured over MesAD, thus resulting in a shorter retention time and poses a higher possibility to increase the organic loading rate (El Mashad et al., 1994; Angelidaki et al., 2006; Esposito et al., 2011), (ii) TherAD has a higher rate of organic matter degradation with a higher biomethane production (Gavala et al., 2003; Labatut et al., 2014; Suhartini et al., 2014), and (iii) TherAD holds a better potential to inactivate pathogens, thus complying with the EU policy for

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elimination of pathogens as well as obtaining Class A biosolids according to the USEPA guidelines (Labatut et al., 2014; Suhartini et al., 2014; Wagner et al., 2008; Ziemba and Peccia, 2011).

Despite the mentioned advantages, TherAD also poses some operational disadvantages including: (i) a relatively higher operating cost, (ii) more sophisticated structural facilities, (iii) a lower process stability, and (iv) a higher susceptibility to inhibition due to sudden environmental changes (De la Rubia et al., 2002; Labatut et al., 2014; Kim et al., 2002). Such disadvantages are mostly due to the acceleration of the biochemical reaction rates of the hydrolysis and acidogenesis steps producing higher amounts of ammonia, propionate and long chain fatty acids (LCFA) that are known to cause inhibition of methanogenic activity (Kastner et al., 2012; Labatut et al., 2014; Scaglia et al., 2014). Thus, in practice MesAD is preferred over TherAD for prolonged operation of AD of FW.

Coupling the advantages of TherAD with those of MesAD in the same digester could result in an enhanced process; although such a combination has been poorly studied. Therefore, this research aims at investigating the effect of applying thermophilic/hyperthermo philic digestion for a short time prior to mesophilic digestion to potentially accelerate the AD process. This was referred to as thermophilic pretreatment (TPP) in this research. The results from TPP (a combination of biological and thermal pretreatment) were compared with conventional thermal pretreatment (CTP), which heats only the FW without inoculum to 50–80 °C prior to MesAD. CTP is one of the easiest and most studied pretreatment methods with proven results even at full-scale. CTP of FW with an aim to improve hydrolysis, increase the biomethane production, and to achieve pasteurization has been studied. Ariunbaatar et al. (2014a) obtained a 52% higher biomethane production with CTP at 80 °C for 1.5 h, whereas Ma et al. (2011) obtained a 24% increase of biomethane production at 120 °C due to enhanced biodegradation of FW. However, CTP at high temperatures (>140 °C) or longer pretreatment times (>4 h) results in the loss of easily fermentable sugars and therefore potential biomethane production (Liu et al., 2012; and Ariunbaatar et al., 2014a).

A series of batch experiments to determine the biomethane potential (BMP) and to compare the effects of CTP and TPP were conducted using a synthetic FW as the substrate. As both the improved hydrolysis and the pathogen inactivation are temperature and treatment time dependent (Boušková et al., 2005), a first set of batch tests was carried out to identify the most favourable temperature range and treatment time of the TPP. The second series of BMP tests was conducted with the aim to compare the effects of TPP and CTP when the operating conditions (temperature and time) were set at the same range. The results were compared with the CTP at 80 °C for 1.5 h, as previous research reported that 52% of biomethane production enhancement was achieved (Ariunbaatar et al., 2014a). Based on these lab-scale experimental data, an energy requirement estimate for the scenarios with the highest biomethane production enhancement by TPP and CTP was done to suggest the most preferable pretreatment method to produce biomethane from FW.

2. Materials and methods

2.1. Pretreatment procedures

To perform the TPP, FW and inoculum were mixed in the BMP bottles, and then incubated at varying temperatures (50, 60, 70 and 80 °C) for a varying time (12, 24, 36 and 48 h). After each TPP, the temperature of the incubator was reduced to mesophilic (35 ± 2 °C) conditions. To perform CTP, only FW was put inside the BMP bottles and directly placed in the incubator at the selected temperatures for the desired time, which was identified during the first set of experiments. The inoculum was added in the bottles after the CTP and incubated at mesophilic conditions. Each test was carried out in duplicate and prior to incubation the BMP bottles were flushed with nitrogen to provide anaerobic conditions. The daily biomethane production was measured with the liquid displacement method using a sodium hydroxide (120 gNaOH/L) solution to capture carbon dioxide (Esposito et al., 2012). During the initial 48 h, the biomethane production was measured every 12 h, and it was measured once a day afterwards until the plateau was achieved. Cumulative biomethane production (CBP) was normalized to standard temperature and pressure.

2.2. Batch BMP experiments of FW

BMP tests were conducted in 1 L glass bottles at mesophilic (35 ± 2 °C) conditions with a substrate to inoculum (*S*/*I*) ratio of 0.5 gVS/gVS, following the BMP protocol described by Esposito et al. (2012). Synthetic FW mimicking a typical European FW was prepared as described by Ariunbaatar et al. (2014a) and used as the substrate. Various foods (fruits, vegetables, meat, rice, paste, and dairy products) were bought from the local supermarkets and blended together for homogenization. The synthetic FW slurry was prepared fresh for each set of experiments. Digestate from a full-scale anaerobic digester in Capaccio–Salerno (Italy) treating buffalo manure and dairy waste at mesophilic conditions was used as inoculum.

2.3. Analytical methods

Soluble chemical oxygen demands (CODs) was analyzed with HACH test kits following the manufacturer's instructions (HACH, Loveland, Colorado, USA). Total lipids were extracted with a mixture of chloroform and methanol (50% v/v). The extracted solution was put in aluminium caps and dried at room temperature in the laminar flow hood until constant weight. The leftover weight was used to calculate the lipids content (Phillips et al., 1997). Total carbohydrates were determined with the phenol–sulfuric method and measured with a spectrophotometer (TUV SR03210002) using glucose as standard solution (Codex Guidelines, 1993). Total solids (TS), volatile solids (VS) and total Kjeldahl nitrogen (TKN) were analyzed according to standard methods (APHA, 2005). Total protein content was calculated based on TKN using a correction coefficient of 6.25, as suggested by CODEX Guidelines, 1993.

2.4. Energy balance calculations

The energy balance of both CTP and TPP was calculated only for the pretreatment step. The energy considerations related to the MesAD operation and the capital cost for the pretreatments were neglected in this study, because the main purpose of the study is to compare the efficiency of the pretreatment methods in terms of enhancing the biomethane production from FW. The energy balance was estimated based on the differences of the total energy requirements for the pretreatment of 1 ton FW, and the extra energy produced (E_{EXTRA}) due to the enhanced biomethane production. E_{EXTRA} and the energy requirement for thermal pretreatment (Ec_{TP}) were calculated as described in details by Ariunbaatar et al. (2014a). The implicit ambient temperature and the initial temperature of the FW were considered as 10 °C. The insulation material for both the digester and the pretreatment chamber for CTP were assumed as polyurethane, as its thermal conductivity is low (0.022 W m^{-1} K^{-1}). The energy requirement for TPP (E_{TPP}) was estimated for the whole digester. Considering the substrate to inoculum ratio of 0.5 gVS/gVS the digester volume was calculated as 31 m^3, which contains 1 ton of FW. Since TPP is conducted