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A new approach for concurrently improving performance of South Korean food waste valorization and renewable energy recovery via dry anaerobic digestion under mesophilic and thermophilic conditions

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ABSTRACT

Dry semicontinuous anaerobic digestion (AD) of South Korean food waste (FW) under four solid loading rates (SLRs) (2.30–9.21 kg total solids (TS)/m^3 day) and at a fixed TS content was compared between two digesters, one each under mesophilic and thermophilic conditions. Biogas production and organic matter reduction in both digesters followed similar trends, increasing with rising SLR. Inhibitor (intermediate products of the anaerobic fermentation process) effects on the digesters' performance were not observed under the studied conditions. In all cases tested, the digesters' best performance was achieved at the SLR of 9.21 kg TS/m^3 day, with 74.02% and 80.98% reduction of volatile solids (VS), 0.87 and 0.90 m^3 biogas/kg $VS_{removed}$, and 0.65 (65% CH_4) and 0.73 (60.02% CH_4) m^3 biogas/kg VS_{fed}, under mesophilic and thermophilic conditions, respectively. Thermophilic dry AD is recommended for FW treatment in South Korea because it is more efficient and has higher energy recovery potential when compared to mesophilic dry AD.

1. Introduction

Food waste (FW) has long been identified as a threat to human health and the environment (Cho et al., 2013; Hamilton et al., 2015; Salemdeeb et al., 2017; Zhang et al., 2011) because it can generate considerable quantities of pathogens, pollutants (greenhouse gases and odorants), and contaminants (organic matter and nutrients) if it is not managed and handled properly. Large quantities of FW are generated every day worldwide through human activities—approximately one-third of food production for human consumption goes to waste (Thyberg and Tonjes, 2016; Uçkun Kiran et al., 2014; Yu et al., 2016). This is equivalent to 1.3 billion tons of food wasted annually (Fisgativa et al., 2016), which is a major contribution to municipal solid waste (Pham et al., 2015; Zhang et al., 2011), possibly up to 45% (Cho et al., 2013). In South Korea, from 2003 to 2014, the amount of FW varied from 4.2 to 5.5 million tons per year (22.46–29.08%, respectively, of municipal solid waste) (Korea Ministry of Environment, 2016). On the positive side, FW does constitute a significant year-round potential source of quality alternative biomass material, as it contains high organic content (in dry matter: 35.5–69% sugar and 3.9–21.9% protein (Uçkun Kiran et al., 2014)) and moisture (75–85%) (Wang et al., 2014a). It is also suitable for biodegradation and renewable energy recovery (Cho et al., 2013; Hamilton et al., 2015; Kim and Oh, 2011; Wang et al., 2014b).

Therefore, utilization of FW can significantly reduce both operating costs of FW treatment plants and damage to the environment and increase economic benefits derived from the production and use of sustainable energy (e.g., subsidies on renewable energy, carbon taxation, carbon credits, etc.). During the last decade, to achieve sustainable waste management strategies, South Korea's government has enforced strict policies that cut production and/or increase recycling of FW (Environment, 2014), such as legislation, regulations, and standards as well as increased disposal fees based on volume (2010) (Cho et al., 2013; Lee and Paik, 2011; Park and Lah, 2015). However, despite urbanization, rapidly rising living standards, and a population explosion from 2010 to 2014 that increased the population by 2.01% (to 50.424 million people,

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2014), it seems the average annual total FW yield did not differ significantly, with 4.99 million tons FW/year (average 0.277 kg FW/person·day) in 2010 and 5 million tons FW/year (average 0.272 kg FW/person·day) in 2014 (Korea Ministry of Environment, 2016). South Korea has the world's largest average ratio of FW generation per capita (Lim et al., 2008).

In South Korea, the most common management solutions for FW are feeding it to animals or using it as fertilizer to improve the structure and increase the porosity of the soil. However, these approaches have become less attractive, due to newly issued regulations as well as limitations in the quality of products and in the control of potentially hazardous pathogens and antibiotic-resistant genes (Kim and Oh, 2011; Wang et al., 2014a; Zhang et al., 2016, 2011). Meanwhile, landfilling or burning of FW has been banned since 2005 (Cho et al., 2013; Lim et al., 2008). Therefore, with the aim of creating a sustainable economy and society, the government's objectives are to develop efficient, economical, mitigative technologies and alternative methods for simultaneous FW valorization and enhanced renewable energy generation. This plan is for both now and in the future, to offer solutions for improving the current treatment system (Cho et al., 2013; Lim et al., 2008). For the purpose of organic waste management and renewable energy recovery, anaerobic digestion (AD) technology has been rated as an effective method and widely applied in practice (Bohutskyi et al., 2015; Gonzalez-Fernandez et al., 2015; Zhang et al., 2011). Currently, depending on the content of total solids (TS) in the raw biomass, AD technology is basically divided into three categories: wet ($\leq$10% TS), semidry (10–20% TS), and dry ($\geq$20% TS) processes (Abbassi-Guendouz et al., 2012). Wet AD has been studied widely in recent years for the treatment of FW or mixtures of FW with other types of waste, such as garden waste, livestock manure (cows, horses, pigs and chickens), sewage sludge, etc. (Fitamo et al., 2016; Wang et al., 2014b; Zhang et al., 2016), with the results indicating that volatile solids (VS) reduction and methane (CH_4) production rate could reach 75% and 0.51 L CH_4/g VS, respectively. However, many problems are associated with this type of digester; for example, they require large volumes and are sensitivities, and failure may even occur if there are changes during system operation. These changes include variations in organic loading rate, ammonia nitrogen (NH_4-N) concentration, pH, volatile fatty acids (VFAs), heavy metals, alkalinity, etc. (Fisgativa et al., 2016; Forster-Carneiro et al., 2008).

In recent years, several studies on dry AD under mesophilic (20–45 °C) or thermophilic (41–70 °C) conditions have been conducted on the organic fraction of municipal solid waste (Benbelkacem et al., 2015; Fernández et al., 2008), lignocellulosic substrates (Brown et al., 2012), and FW (Cho et al., 2013). All of these have generally demonstrated the dry AD technology's economical and engineering feasibility and report several advantages and benefits, such as high organic loading rate, high biogas volumetric efficiency, low water content, and small digestate. However, dry AD does have several limitations that need to be overcome, for instance, long startup and degradation times and sensitivity to inhibitors, which are intermediate products of the anaerobic fermentation process (Banks et al., 2011; Forster-Carneiro et al., 2008; Huang et al., 2016).

Although dry AD has received special attention from the global scientific community recently, there seems to be no consistency among the early studies (Banks et al., 2011; Fernández et al., 2008), due to their heterogeneity of experimental conditions, e.g., variations in the environmental conditions, physicochemical characteristics of the substrates, seasons, regions, cultures, policies, etc. (Cho et al., 2013; Thyberg and Tonjes, 2016; Uçkun Kiran et al., 2014; Zhang et al., 2007). Furthermore, no studies to date have calculated the recoverable FW energy potential of dry AD. Generally, available information in the literature concerning dry AD under thermophilic and mesophilic conditions in the field of valorization and conversion of FW for renewable energy recovery is very limited; thus, the exact mechanisms of such are not fully understood. Additionally, FW characteristics are the main factors directly affecting the anaerobic decomposition process (Uçkun Kiran et al., 2014; Zhang et al., 2007). For this reason, research on dry AD for South Korean FW is urgently needed. The results of the present study should provide a more effective solution for South Korea's Waste-to-Energy mandates as well as valuable information to the global scientific community.

Therefore, the purposes of this research were to: (1) examine the performance of thermophilic and mesophilic dry AD for FW valorization under solids loading rates (SLR) that were increased stepwise from 2.3 to 9.21 kg TS/m^3 day at a fixed TS content of 22%; (2) evaluate the biogas production and organic matter reduction during each process phase; (3) explain the relationship between SLR and renewable energy production; (4) evaluate the potential for converting South Korea's FW into renewable energy via dry AD under different conditions; and (5) estimate electricity generation from the biogas produced using these treatment technologies for FW. In addition, the influence of the intermediate products of the AD process on the operational performance of the digesters was investigated.

2. Materials and methods

2.1. Characteristics of the FW and inoculums

The corresponding FW and inoculum used in this study were obtained from the student cafeterias located in Kyonggi University, South Korea and a large-scale mesophilic dry AD plant of FW in "P" city, South Korea, respectively. Immediately after collection, the raw FW was crushed into particles smaller than 2 mm in size by a crusher and stored in a refrigerator (0–4 °C) prior to the dry AD experiments.

The main characteristics of TS, VS, VS/TS ratio, total chemical oxygen demand (TCOD), total nitrogen (TN), NH_4-N, and C/N ratio of the FW and inoculum are outlined in Table 1 and described in our previous work (Nguyen et al., 2017; Nguyen et al., 2016).

2.2. Experimental setup and operational conditions

Two independent, dry, semi-continuous anaerobic digesters were operated under mesophilic (38 °C) and thermophilic (55 °C) conditions (Fig. 1). The total and effective volumes of each dry anaerobic digester were 20 L and 10 L, respectively. The digesters were mounted with a hot water jacket system to control the operating temperature, which was set in advance depending on each digester's requirements; an agitator to mix the contents completely (anaerobic microbes, substrates, etc.) at a constant

Table 1
Characteristics of the food waste and inoculum used for the dry AD experiments.

Parameters	Unit	Food waste	Inoculum
pH	–	4.91	7.62
Total solids (TS)	%	23.02 (2.22)	20.02
Volatile solids (VS)	%	20.55 (0.84)	12.59
VS/TS	%	91.53 (2.34)	69.54
Total chemical oxygen demand (TCOD)	mg/kg	220,000 (5739)	72,000
Total nitrogen (TN)	mg/kg	3650 (162)	4200
Ammonia nitrogen (NH_4-N)	mg/kg	900 (187)	1800
C/N ratio	–	14.58	–

The standard deviation are in parentheses.