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Effect of hydrothermal pre-treatment (HTP) on poultry slaughterhouse waste (PSW) sludge for the enhancement of the solubilization, physical properties, and biogas production through anaerobic digestion

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ABSTRACT

This study is an assessment of the hydrothermal pre-treatment (HTP) of poultry slaughterhouse waste (PSW) sludge for the enhancement of the solubilization, physical properties, and biogas production through anaerobic digestion. This assessment was carried out to ascertain the optimal HTP temperature. The solubilization and physical properties efficacy was investigated by capillary suction time (CST), time to filter (TTF), and particle size. In addition, the anaerobic digestion was investigated through biochemical methane potential (BMP) tests and subsequent statistical analysis using the modified Gompertz model. HTP was found to have improved the solubilization of the PSW sludge with increasing HTP temperature. In addition, the results of the CST, TTF, and particle size decreased with increasing HTP temperature. These results of the assessment that was conducted in this study confirm that the HTP process indeed modifies the physical properties of PSWs to enhance the solubilization of organic solids. Nevertheless, the results of the BMP tests and the modified Gompertz model analysis show that the optimal HTP temperature of PSWs for anaerobic digestion is 190 °C. These findings show that to achieve high conversion efficiency, an accurately designed pre-treatment step must be included in the overall anaerobic digestion process for wastewater treatment.

1. Introduction

In the past decade, the poultry consumption in South Korea increased rapidly from 6.9 kg person^{-1} (year 2000) to 10.7 person^{-1} (year 2010). As a result of the growth in the poultry industry, high amounts of organic solid by-products, which are considered industrial organic wastes, are generated from poultry slaughterhouses (Salminen et al., 2002). These organic solid wastes need to be strictly managed by governmental legislation. Until now, however, the organic solid wastes from poultry slaughterhouses have mainly been recycled as animal feedstock through the rendering process. These organic solid wastes generated from slaughterhouses, however, were a good substrate for anaerobic digestion producing biogas, and anaerobic digestion has been considered one of the best alternatives (Kaparaju et al., 2010).

Anaerobic digestion can be a solution for treating organic waste as it can stabilize sludge, reduce solids, and produce biogas, even though the process has the limitations of long retention times and the low overall degradation efficiency of the organic matter. As most of the organics present in poultry slaughterhouse wastes (PSWs) are slowly biodegradable, the rate-limiting step in PSW digestion is the hydrolysis of organic matter (Park and Kim 2015; Park et al., 2016). Thus, various technologies have been developed to improve the biodegradability of complex wastes through the application of different pre-treatment methods (Park et al., 2016). Various pre-treatment methods, including the biological (Ehimen et al., 2013), mechanical (e.g., ultrasonic, microwave pre-treatment) (Eskicioglu et al., 2009; Ehimen et al., 2013), chemical, and thermal methods (as autoclave, <170 °C) (Ariunbaatar et al., 2014), have been investigated. Pre-treatment improves the overall digestion process's velocity, efficiency, and sludge reduction, thereby reducing the anaerobic digester retention time and increasing the methane production rates (Mottet et al., 2009; Erden et al., 2010; Braguglia et al., 2012).

Among the thermochemical pre-treatment methods, hydrothermal pre-treatment (HTP) is an effective technique for achieving organic matter degradation (Park and Kim, 2015). This allows the complex organic molecules (e.g., carbohydrates, lipids, proteins,

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and nucleic acids) to be released from the solids and be broken down. These hydrolysates can then be utilized by the extracellular enzymes produced by anaerobic microorganisms, leading to improved anaerobic digestion (Wang et al., 2009). The efficiency of the HTP process prior to anaerobic digestion has prompted many to develop a relevant technology (Zheng et al., 1998; Wang et al., 2010). In HTP, a combination of high-temperature and high-pressure subcritical water (180 °C < T < 373 °C) is used to efficiently achieve hydrolysis, solubilization, and solid destruction (Mursito et al., 2010), which the reaction to HTP commonly starts at approximately 180 °C (Funke and Ziegler, 2010). Such hydrothermal methods are advantageous in that they do not require chemical catalysis, thus reducing the associated costs and being more environment-friendly.

In this study, HTP was applied prior to the anaerobic digestion of organic solid wastes from PSWs to improve the biogas production and digestion ratio. The effect of the pre-treatment temperature (170–220 °C) on the characteristics of organic matter was determined, and the efficiency of biogas production was evaluated, through the biochemical methane potential (BMP) test.

2. Materials and methods

2.1. Slaughterhouse wastes

The selected PSWs were sampled at a poultry slaughterhouse facility with a slaughtering capacity of 120,000 heads per day located in Jincheon, South Korea. The processes employed by the slaughterhouse facility consisted of mooring, slaughtering, bleeding, scalding, picking and singeing, evisceration, washing, chilling, and further processing for meat cutting and deboning, in that order. The characteristics of PSWs are shown in Table 1.

2.2. Experiment set-up

2.2.1. Hydrothermal pre-treatment process

HTP experiments were performed using a 500 mL lab-scale reactor. The reactor consisted of a reactor body, a heater, and a steam condenser, and was operated under N_2 gas. For all the experiments, 200 ml feedstock was loaded into the reactor, with equal amounts of water. The HTP operating temperatures and pressures ranged from 170 to 220 °C and 1.7–2.0 MPa, respectively, and the reaction time was 30 min. The components in the reactor were mixed using an agitator rotating at 200 rpm. After the completion of the hydrothermal reaction, the residual steam was discharged from the reactor, and the reaction products were removed.

Table 1
Characteristics of poultry slaughterhouse wastes.

Parameter	Unit	Value (average ± S.D)
Total COD	g/L	26.8 ± 3.04
Soluble COD	g/L	0.6 ± 0.1
pH	–	6.5 ± 0.2
TS	w/w, %	20.4 ± 0.96
VS	w/w, %	18.2 ± 0.11
VS/TS	%	88.9 ± 0.13
TN	g/kg	13.7 ± 0.31
NH_4^+-N	g/kg	2.6 ± 0.15
TP	g/kg	2.8 ± 0.035
NaCl	g/kg	0.6 ± 0.012
K	mg/kg	360
Ca	mg/kg	294
Mg	mg/kg	248
Na	mg/kg	549
Fe	mg/kg	587
Co	mg/kg	0.13
Ni	mg/kg	13.87
Cu	mg/kg	49.96
Zn	mg/kg	88.89

S.D: standard deviation, COD: chemical oxygen demand, TS: total solid, VS: volatile solid, TN: total nitrogen, TP: total phosphorus, 1% = 10,000 mg/L.

Table 2
Characteristics of the anaerobic inocula.

Parameter	Unit	Value (average ± S.D)
pH	–	8.4
TS	g/L	17.0 ± 0.477
VS	g/L	10.6 ± 0.399
TKN	g/L	5.1 ± 0.246
NH_4^+-N	g/L	3.4 ± 0.033
Alkalinity	g/L as $CaCO_3$	6.9 ± 0.208

2.2.2. Biochemical methane potential (BMP) test

The anaerobic methane production was assessed using a batch anaerobic reactor under mesophilic conditions (38 °C). Sludge for feed was also sampled for digestibility comparisons with PSWs pre-treated under various temperatures (170, 180, 190, 200, and 220 °C). Inocula were collected from a farm-scale biogas plant (Anseong, South Korea) that digested pig slurry. The characteristics of the inocula are shown in Table 2. The inoculum samples collected from the anaerobic digester were sieved at 2 mm, and before initiating the BMP assay, 2L inoculum samples were pre-incubated in a 5L anaerobic batch reactor under mesophilic conditions (38 °C) to deplete the residual biodegradable organic matter present therein. Thereafter, pre-incubated digestate was prepared as an inoculum for BMP assay. Subsequently, the fermented digestate was prepared as an inoculum for BMP assay. The substrate-to-inoculum ratios of all the BMP assay cultures were equal to 0.3 g-$VS_{substrate}$/g-$VS_{inoculum}$, and the BMP assays were carried out in an 80 mL working volume, using a 160 mL serum bottle. Methanogenic bacterial is extremely sensitive to pH fluctuations and prefer pH around 7.0 as the growth rate of methanogens (Park et al., 2016). Base on the study of Park et al., at a lower pH of 6.7 and a high a pH of 8.5 the methane yield was much lower (Park et al., 2016). Therefore, A 6 g/L $NaHCO_3$ concentration in the bottle was used to prevent pH decrease (Park et al., 2016). The head space of the serum bottle was filled with N_2 gas and was sealed with a butyl rubber stopper. Three BMP bottles for each sample were incubated up to 48 days for all the pre-treatment schemes in this study. The biogas produced from the inocula and media were recorded and used as blanks in the assay. The methane production was corrected for the standard temperature and pressure (STP), and the BMP was determined by the unit of the VS content of waste added to the vial. To describe the progress of the cumulative methane production, the modified Gompertz equation (Eq. (1)) was employed to fit the cumulative methane production data, as follows (Costa et al., 2012).

$$M = P \times \exp\{-\exp[Rm \times e/P \times (\lambda - t) + 1]\} \quad (1)$$

where M is the cumulative methane production (mL), e is exp (1), Rm is the maximum specific methane production rate (mL/d), P is the methane production potential (mL), and λ is the lag phase time (days).

The kinetics constant M, Rm and λ were determined using non-linear regression approach for the best fittings with the aid of solver command in Microsoft excel (Park et al., 2016). We estimated the model parameters in Eq. (1) using least-square estimation. This equation was utilized by researchers to study the cumulative methane production in biogas production. Lay et al. (1996) applied this equation to study bacteria growth (Lay et al., 1996).

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