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Anaerobic co-digestion of steam-treated *Quercus serrata* chips and sewage sludge under mesophilic and thermophilic conditions

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HIGHLIGHTS

- Steam explosion pretreated *Quercus serrata* chips were co-digested with sewage sludge.
- Un-treated chips inhibited the methane production.
- Steam explosion improved the biodegradability of the chips considerably.
- Thermophilic condition was favorable for the biodegradation of the chips.
- Methane conversion ratio increased with the decrease of acid-soluble lignin content.

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ABSTRACT

The biodegradation of *Quercus serrata* chips was evaluated by anaerobic digestion under various steam explosion conditions. In continuous experiments, untreated chips (W_0) and chips steam-treated at less than 1.0 MPa (W_1) and 2.0 MPa (W_4) were co-digested with sewage sludge (S_1 and S_2) taken from two different wastewater treatment plants. The apparent methane yield of W_1 and W_4 co-digested with S_1 (thermophilic) was 261 dm^3/kg VS (volatile solids) and 248 dm^3/kg VS, respectively. The apparent methane yield of W_4 co-digested with S_2 was 258 dm^3/kg VS (mesophilic) and 271 dm^3/kg VS (thermophilic). Methane production was inhibited by W_0 due to components released during hydrolysis. The methane conversion ratio of pretreated chips obtained in batch experiments varied from 40.5% to 53.8% (mesophilic) and from 49.0% to 63.7% (thermophilic). The methane conversion ratio increased with decreasing acid-soluble lignin content in the chips.

1. Introduction

Anaerobic digestion, which treats various organic waste and plant biomass as feedstock, is one of the most economical technologies for recycling energy and reducing greenhouse gas emissions (Dhingra et al., 2011). Anaerobic digestion has been widely employed in wastewater treatment plants (WWTPs) for the digestion of sewage sludge. The introduction of additional organic waste to the digester has been found to be beneficial owing to the production of extra biogas (Pahl et al., 2008; Hidaka et al., 2013). Woody waste from greenery is potential feedstock for anaerobic digestion. Currently, the amount of woody waste produced in Japan is estimated to be 31.7 Tg/year on a dry-weight basis, equivalent to approximately 2.8% of the national primary energy supply (Yoshioka et al., 2005). Among various trees, *Quercus serrata* is a common plant distributed throughout Japan, and its chips can be collected from public green spaces such as roadsides, gardens, and parks. If *Q. serrata* chips are used as a feed substrate in an anaerobic digester, more biogas could be produced by introducing such biomass to a sewage treatment facility.

Despite its potential biodegradability, the production of biogas from woody waste tends to be low because of its high lignocellulose biofiber content (Klimiuk et al., 2010). Lignocellulose is insoluble in water because of its complex polymer network of cellulose, hemicellulose, and lignin. Also, it has a complex and rigid structure that is resistant to enzymatic attack during anaerobic digestion. Hence, pretreatment is necessary to increase the biodegradability of such woody waste before anaerobic digestion. Steam explosion is considered to be one of the most effective pretreatments for the digestion of woody biomass (Asada et al., 2012). In steam explosion treatment, the substrate is treated at high temperature and pressure, and after a set treatment time, steam is rapidly released. Treatment using steam explosion enhances the hydrolysis of lignocellulose, thereby increasing the biodegradability of the substrate.

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The effectiveness of steam explosion is affected by various parameters such as pressure and temperature, treatment time, catalyst type and dosage, and substrate characteristics (Horn et al., 2011). Numerous studies have reported the effects of steam explosion on the biodegradability of biomass waste with high lignocellulose content. The temperature employed in steam explosion is typically between 160 and 260 °C with a treatment time of a few seconds to several minutes (Taherzadeh and Karimi, 2008). Ochi et al. (2004) demonstrated that steam explosion improved the biodegradability of beech and oak chips and achieved the optimum biodegradation result at a pressure of 2 MPa with a retention time of 15 min. Wang et al. (2010) investigated the anaerobic digestion of bulrush under steam explosion and obtained a maximum methane yield of 205.3 ml/g VS at a moisture of 11.0%, a steam pressure of 1.72 MPa, and a residence time of 8.14 min. Bruni et al. (2010) treated biofibers from digested manure for 15 min with steam in a pressure vessel at 155 °C with the addition of 2.1% w/w H_2SO_4, and obtained an increase in methane production of up to 67% from steam-treated biofibers compared to untreated biofibers. Estevez et al. (2012) conducted batch experiments to evaluate the effect of steam explosion on the methane production of *Salix* and found that steam explosion increased methane yield by up to 50%, with the best results obtained with temperatures starting at 210 °C. However, harsh steam conditions of high pressure and temperature increase the required energy and cost, and some components such as vanillin, vanillin alcohol, furfural, and HMF (Ramos, 2003) are generated during the treatment process, which have an inhibitory or toxic effect on methanogens (Gossett et al., 1982); hence, mild steam treatment is preferable.

The dewaterability of digested sludge is of significant concern in practical operation. Previous studies have demonstrated that fibers can improve the dewaterability of sludge by increasing the rigidity of the sludge, leading to good solid recovery (Hashimoto and Hiraoka, 1990). Biomass with high fiber content is expected to improve sludge dewaterability; however, there have been few detailed reports on steam-treated wood chips.

Furthermore, several studies have indicated that a thermophilic temperature range is preferable for anaerobic digestion processes caused by its superior performance to mesophilic digestion (Angelidaki et al., 2006; Coelho et al., 2011), even though the majority of anaerobic digesters are operated under mesophilic conditions. Although thermophilic conditions are preferable for the hydrolysis of lignocellulose structures and subsequent biogas production, previous studies have mainly discussed the biodegradation of steam-treated samples under mesophilic batch conditions. The biodegradation of woody waste under continuous thermophilic anaerobic conditions has rarely been discussed.

This study evaluates the biodegradation of steam-treated *Q. serrata* chips under mesophilic and thermophilic anaerobic co-digestion with sewage sludge. In continuous experiments, the chips and sewage sludge were co-digested, and reactor performance including methane yield per added VS and dewaterability was compared. Using digested sludge adapted to *Q. serrata* chips, the inhibitory effect of untreated *Q. serrata* chips on methane production was evaluated by batch experiments, and a biochemical methane potential (BMP) assay was conducted to evaluate the methane conversion of chips and the effect of lignin content on the biodegradability of the chips.

Table 1
Steam explosion treatment conditions for *Quercus serrata* chips.

Chip	Treatment step	Pressure (MPa)	Temperature (°C)	Duration (min)
W_1	–	0.8–1.0	171–179	60
W_2	–	0.9	178	180
W_3	1	–	Increased to 213 (without pressurization)	15
	2	0.9	178	60
W_4	–	2.0	213	15

2. Methods

2.1. Preparation of Q. serrata and sewage sludge

Q. serrata chips were collected from a park. W_0 denotes chips shredded into approximately 10-mm-long small pieces without steam explosion. The steam explosion treatment of W_0 was conducted in a 30-L stainless (SUS316) reactor with a 40-kW electrical boiler under four different conditions (W_1–W_4) (Table 1). The treatment conditions of W_1 and W_2 were 0.8–1.0 MPa and 171–179 °C for 60 min and 0.9 MPa and 178 °C for 180 min, respectively. These pressures and temperatures were lower than those employed in typical steam explosion treatments however, Japanese regulations on pressure vessels are less stringent for pressures of less than 1.0 MPa, and waste heat can be used more effectively at low temperatures. Steam treatment for W_3 consisted of two procedures: the temperature was increased to 213 °C without pressurization and maintained for 15 min. Then, steam explosion treatment was performed at 0.9 MPa and 178 °C for 60 min. The condition for W_4 was 2 MPa and 213 °C for 15 min. Ochi et al. (2004) showed that this condition was favorable for the pre-treatment of wood for anaerobic digestion.

Sewage sludge (S_1 and S_2) consisted of a mixture of primary sludge and waste-activated sludge was taken from two different WWTPs, respectively. The original total solids (TS) content of S_1 and S_2 was 1–2% and 2–3%, respectively. Prior to the experiments, the sludge was centrifuged at 3000 rpm for 10 min, and the supernatants were discarded to obtain a TS content of around 4%. The characteristics of *Q. serrata* chips and sewage sludge are summarized in Table 2.

2.2. Continuous experiments

Four lab-scale continuously stirred tank reactors (R_1, R_2, R_3 and R_4) were operated (Table 3). All of the reactors were cylindrical,

Table 2
Characteristics of sewage sludge and chips (average value ± SD).

Items	Unit	S_1	S_2	W_0	W_1	W_2	W_3	W_4
pH	–	5.83 ± 0.01	5.64 ± 0.05	–	–	–	–	–
TS	%	3.6 ± 0.5	4.0 ± 0.7	84.4 ± 1.6	25.0 ± 2.7	19.3 ± 1.5	35.6 ± 0.5	45.3 ± 0.7
VS	%	3.0 ± 0.4	3.4 ± 0.6	83.6 ± 1.5	24.6 ± 2.7	19.0 ± 1.5	34.5 ± 0.6	43.6 ± 0.5
T-COD	g/L	46.7 ± 10.0	63.4 ± 9.7	–	–			–
T-COD	g/g-VS	–	–	1.11 ± 0.08	1.16 ± 0.08	1.35 ± 0.11	1.39 ± 0.03	1.44 ± 0.16
C	% (dry)	40.6 ± 0.1	44.4 ± 0.01	47.5 ± 0.05	50.2 ± 1.2	51.6 ± 0.7	52.9 ± 0.5	51.8 ± 0.08
H	% (dry)	6.20 ± 0.04	6.72 ± 0.38	6.17 ± 0.30	6.20 ± 0.61	6.02 ± 1.01	5.97 ± 0.22	6.09 ± 0.20
N	% (dry)	4.60 ± 0.04	5.34 ± 0.32	N.D.*	N.D.	N.D.	N.D.	N.D.

* Not detected.