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Effects of organic loading rates on reactor performance and microbial community changes during thermophilic aerobic digestion process of high-strength food wastewater

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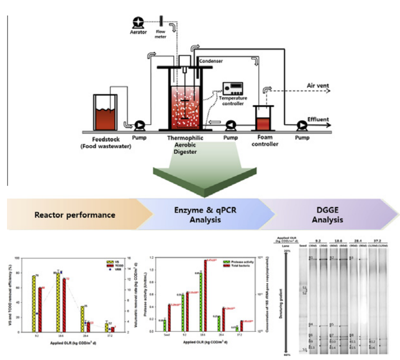
HIGHLIGHTS

- Applicability of a TAD process was evaluated for the treatment of high-strength FWW.
- The OLR of 18.6 kg COD/m^3 d was the best among various conditions for FWW treatment.
- Protease activity and VRR were closely associated.
- The changes of OLRs significantly affected the microbial community changes.
- The Firmicutes were the main contributors in treating high-strength FWW.

GRAPHICAL ABSTRACT



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ABSTRACT

To evaluate the applicability of single-stage thermophilic aerobic digestion (TAD) process treating high-strength food wastewater (FWW), TAD process was operated at four organic loading rates (OLRs) from 9.2 to 37.2 kg COD/m^3 d. The effects of OLRs on microbial community changes were also examined. The highest volumetric removal rate (13.3 kg COD/m^3 d) and the highest thermo-stable protease activity (0.95 unit/mL) were detected at OLR = 18.6 kg COD/m^3 d. Denaturing gradient gel electrophoresis (DGGE) profiles and quantitative PCR (qPCR) results showed significant microbial community shifts in response to changes in OLR. In particular, DGGE and phylogenetic analysis demonstrate that the presence of *Bacillus* sp. (phylum of Firmicutes) was strongly correlated with efficient removal of organic particulates from high-strength food wastewater.

1. Introduction

Over the past decade, with the marked increment of population and living standards, a large amount of food waste has been generated in worldwide. According to recent reports, one third of the edible food produced for human consumption has been wasted globally, which is estimated about 1.3 billion tons per year (Gustavsson et al., 2011). In Korea, about 4 million tons of food wastes per year have been generated and Korean government

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implements numerous food waste management projects (MOE, 2012) due to the fact that inappropriate management could lead to environmental problems and public nuisances such as groundwater contamination, attracting vermin and rise of malodor (Shin et al., 2001). In this regard, 260 food waste recycling facilities were installed and operated by Korean government (MOE, 2012). In these facilities, most of food waste is recycled as feedstuff and fertilizer. During the recycling process (i.e., storage, separation and washing step), a large amount (approximately 9398 tons/d) of secondary pollutant, food wastewater (FWW), which has high-strength organic matter and salt is generated (MOE, 2012). Generally, most of FWW had been discharged to the ocean before 2013, however it was completely prohibited in January of 2013 by the London Convention 97 protocol, because this disposal method posed serious problems with marine environment (MOE 2012). Therefore, finding and developing an effective FWW treatment method has become an urgent challenge.

Biological treatment is considered to be a practical approach to treat high-strength wastewater. In large-scale wastewater treatment plants (WWTPs), anaerobic treatment is more preferred because it generates a considerable amount of recoverable biogas (e.g., CH_4 or H_2). However, it is not an economical option in medium- and small-scale WWTPs because it require relatively long retention time and high capital cost (Metcalf and Eddy, 2004). Therefore, aerobic treatment will be more suitable and easy to implement in the medium- and small-scale WWTPs than is anaerobic treatment. One potentially attractive option is thermophilic aerobic digestion (TAD), which has four obvious advantages: self-heating, rapid biodegradation rate, low biomass production (Kelly et al., 1993), and efficient elimination of pathogen due to the high operating temperature (>55 °C) (Liu et al., 2012). These potential advantages indicate that TAD could be a practical alternative for treating high-strength FWW.

Due to significant advances in optimization of TAD technology and in the effectiveness of organic matter removal, TAD has been employed for treating high-strength organic wastes, which mainly derived from agriculture or food industry effluent, such as swine waste, brewery and slaughterhouse effluent (Couillard et al., 1989; Beaudet et al., 1990; Zvauya et al., 1994). TAD was adapted from traditional aerobic digestion and has been normally composed of two-stage or multi-stage processes to achieve sufficient removal of organic materials (Skjelhaugen, 1999). However, due to significant advances in aeration and reactor optimization technology, single-stage TAD has been developed. If the process conditions are controlled correctly, single-stage TAD can achieve sufficient removal efficiency and its microbial community structure similar to those in two-stage TAD (Skjelhaugen, 1999; Liu et al., 2010).

Microbial community structures in TAD have been reported for TAD systems treating various organic wastes (LaPara et al., 2002; Juteau et al., 2004; Piterina et al., 2010) to identify consortiums of TAD bacteria and to obtain insight into mechanisms by which these consortiums are stabilized. Generally, these studies reported that TAD shows low levels of biodiversity, that several species can produce thermo-stable hydrolytic enzymes (Kim et al., 2002; Li et al., 2009), and that microbial community structure in TAD can shift with changes in digestion conditions (e.g., temperature or organic loading) or feedstocks (Hayes et al., 2011). However, to our best knowledge no study has reported microbial community structure during TAD process of high-strength FWW.

The primary goal of the present study was to evaluate the feasibility of single-stage TAD treatment of high-strength FWW and the effects of organic loading rates (OLRs) on process effectiveness. Also, when evaluating the process, it is quite important to investigate the correlation between the reactor performance and microbial community structure. Therefore, in this study we also evaluated the microbial community changes under different OLRs.

2. Methods

2.1. Preparation of feedstock

The feedstock was collected from a food-waste recycling facility in Pohang, Korea. This facility treats 180 tons/d of food waste and generates 50 tons/d of FWW during the process. The FWW sample was filtered through a 1.0-mm sieve to remove inert materials, then distributed in 3-L bottles and stored at −25 °C until use. To control the OLRs, FWW was diluted with deionized water (DW). Dilution reduced the concentration of organic materials in FWW but did not greatly affect its pH. More detailed dilution rate and physic-chemical characteristics of the FWW used in this study are presented in Table 1.

2.2. Bioreactor setup and operation

The experiment was conducted in a lab-scale semi-continuous TAD reactor (Fig. 1), which was operated with working volume of 1.5 L and equipped with a condenser. The reactor was seeded with TAD sludge taken from a successfully-operated autothermal thermophilic aerobic digestion (ATAD) pilot plant in Daejeon, Korea. This plant use AFC® process (PMC BioTec Co.) to treat 3 m^3/d of sewage sludge. To allow the seed microorganism to acclimatize, the reactor was operated in batch mode for one week before initiation of semi-continuous operations. The reactor was fed four times a day using a peristaltic pump (Cole-Parmer®) controlled by a timer and relay. Four different OLRs (9.2, 18.6, 28.4 and 37.2 kg COD/m^3 d) were applied sequentially over a period of 120 d. The reactor was operated at thermophilic temperatures (55 ± 0.5 °C) with 5-d hydraulic retention time (HRT); compressed air was continuously supplied at 10 L/min through a fine-pore diffuser to maintain aerobic conditions. Owing to continuous aeration and high lipid concentration in the feedstock, excessive foaming occurred during the digestion, thus a foam controller was installed; all excess foam was immediately recycled into the reactor to maintain reactor volume.

2.3. Physical–chemical analytical method

Total solids (TS), volatile solids (VS), total chemical oxygen demand (TCOD), total alkalinity (TA), total nitrogen (TN), and total phosphorus (TP) were measured in accordance with the Standard Methods (APHA-AWWA-WEF, 1998). For measurement of soluble COD (SCOD), ammonium (NH_4^+-N), soluble TN (STN), and soluble TP (STP), samples were filtered through a 0.45-μm pore-size filter. The soluble carbohydrate and protein concentrations were measured as described in previous research (Jang et al., 2013). After passing the sample through a 0.45-μm pore size filter, lipid concentrations were determined according to the method of Bligh and Dyer (1959) using a chloroform–methanol (1:2 v/v) solvent. The anion concentrations including nitrite (NO_2^-), nitrate (NO_3^-), and orthophosphate (PO_4^{3}-P) were determined using an ion chromatograph (ICS-1000, DIONEX Co., USA). The pH in the reactor was continuously monitored using a pH meter (405-DPAS-SC-K85, METTLER TOLLEDO, Switzerland). Organic acids were quantified using a high performance liquid chromatograph (HPLC, Agilent Technology 1100 series, Agilent Inc., USA) equipped with an organic acid and alcohol analysis column (Aminex HPX-87H, BIORAD Inc., USA), a refractive index detector (RID), and a diode array detector (DAD). The quantified values were converted to g COD/L