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Performance and kinetic evaluation of semi-continuously fed anaerobic digesters treating food waste: Role of trace elements

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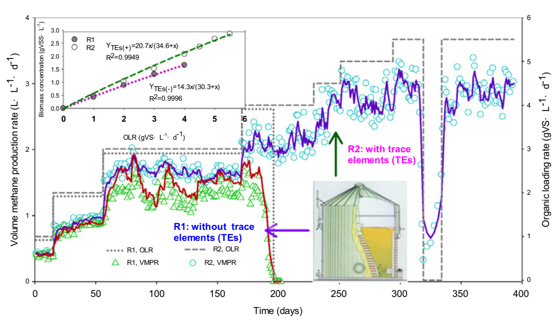
HIGHLIGHTS

- The AD of food waste was severely acidified due to lack of essential TEs.
- TEs addition improved operation stability of AD of food waste at higher OLRs.
- Deficiency of Se resulted in accumulation of both acetic and propionic acids.
- Higher methane yield coefficient and biomass yield was achieved with TEs addition.

GRAPHICAL ABSTRACT



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ABSTRACT

This study investigated the effects of trace elements (TEs) on the anaerobic digestion (AD) of food waste (FW) in laboratory-scale semi-continuously fed anaerobic digesters. The duration of digesters operation was approximately 400 days. Organic loading rates (OLRs) ranged from 1.0 to 5.5 g VS L^{-1} d^{-1} at 37 °C. Results showed that methane production of the digester was severely inhibited at a volatile fatty acid (VFA) concentration of 30,000 mg L^{-1} at OLR of 4.0 g VS L^{-1} d^{-1} in the absence of TEs. Contrary to the failed digesters, a stable performance was achieved in the TEs added digesters. High methane yield (approximately 465.4 mL CH_4 g^{-1} VS_{added}) was obtained, and no significant accumulation of VFA was observed in the TEs added digesters at OLR of 1.0–5.0 g VS L^{-1} d^{-1} and HRT of 40 days. These findings strongly indicated that the addition of TEs has an important impact on the operation stability of AD of FW.

1. Introduction

Anaerobic digestion (AD) has been widely used to treat food waste (FW) because it simultaneously stabilizes and recovers energy from FW (Niu et al., 2013). FW is a highly desirable substrate for biogas fermentation because of its easy bioconversion and high volatile solids (VS) content, but digesters with FW as sole feedstock for biogas production are prone to instability and even process failure because of the absence of trace elements (TEs) (Banks et al., 2012; Climenhaga and Banks, 2008; Lin et al., 2011a; Tampio et al., 2014). It is reported by Climenhaga and Banks (2008) that the digestion of FW without the addition of TEs under mesophilic conditions failed at a relatively low organic loading rate (OLR) of 1.45 g VS L^{-1} d^{-1}. Similarly, Lin et al. (2011a, 2011b) and Tampio et al. (2014) found that the anaerobic digesters with FW as the sole substrate without the addition of TEs failed at the OLRs of 3.0 and 6.0 g VS L^{-1} d^{-1} because of volatile

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fatty acids (VFA) accumulation. These problems potentially limit the application of AD technology in FW treatment because of insufficient TEs.

Trace elements (TEs) serve an important function in the growth of methanogens and are essential co-factors of enzymes, such as methyl-coenzyme M, carbon monoxide dehydrogenase (CODH), and coenzyme M methyl-transferase, which are involved in the anaerobic degradation of biomass (Banks et al., 2012; Karlsson et al., 2012; Pobeheim et al., 2010, 2011; Qiang et al., 2012). TEs, such as iron (Fe), cobalt (Co), nickel (Ni), Selenium (Se), molybdenum (Mo), and/or tungsten (W), are crucial for the activity of enzymes in methanogenic systems (Feng et al., 2010; Oechsner et al., 2008). Food waste (FW) should be co-digested with other feedstock that are rich in TEs or external TE should be added to the digester to ensure the performance stability of the AD system (Banks et al., 2012; Climenhaga and Banks, 2008; Facchin et al., 2013; Qiang et al., 2012; Tampio et al., 2014; Zhang and Jahng, 2012; Zhang et al., 2011). Zhang et al. (2011) found that co-digestion of FW with piggery wastewater remained steady and stable for 367 d because the metal-abundant piggery wastewater supplied the required TEs. Facchin et al. (2013) pointed out that stability improved and methane production increased by 45–65% by adding a TE mixture comprising Co, Mo, Ni, Se, and W. The addition of TEs at an adequate amount could accelerate the degradation of VFA and long chain fatty acids (LCFA) (Karlsson et al., 2012; Vintiloiu et al., 2013). AD performance of FW has been studied previously, but information is lacking on the effect of TE addition on the AD of FW with high solid and crude fat contents.

Kinetic analysis is an accepted method of describing the performance of biological treatment systems and of predicting their performance (Guo et al., 2013a; Lin et al., 2011b; Wang et al., 2009). Kinetic models, such as the Monod first-order, Stover–Kincannon, substrate mass balance models, have been used to determined the kinetic constants and thereby evaluate the performance of different types of digesters (anaerobic moving bed biofilm reactor, continuous stirred tank reactor, etc.) and feeding substrates (pulp & paper sludge, pig manure, etc.) (Guo et al., 2013a, 2013b; Lin et al., 2011b; Wang et al., 2009). Although the biogas production process of FW has been studied, no kinetic analysis has been reported on the substrate utilization and methane production of the AD of FW with the addition of TEs.

This study aimed to verify the effect of adding TEs (Fe, Co, Ni, and Se) on the recovery of unstable AD systems for FW treatment and to identify the key TE involved in the recovery process at high organic loading rate (OLR). In addition, a kinetics analysis was conducted to determine the different kinetic constants with and without TEs addition. Such analysis is expected to clearly explain the effects of TEs.

2. Methods

2.1. Materials and digesters

The food waste (FW) used in this study was collected from a restaurant in the campus of China Agricultural University, Beijing, China. The non-biodegradable contaminants in the FW were removed, after which the FW was crushed using an electrical kitchen blender (JYL-A100, Jinan, China). The homogenized samples were frozen at −20 °C to prevent biological decomposition, and the frozen substrates were thawed in a refrigerator at 4 °C for 1 day before they were used. The inoculum (seed sludge) was collected from an anaerobic digester in the Xiaohongmen municipal wastewater treatment plant located in southern Beijing, China. The characteristics of the FW and inoculums are listed in Table 1.

Table 1
Characteristics of food waste (FW) and inoculum.

Parameter	Food waste	Inoculum
TS (%FM)	21.75 (0.34)	2.23 (0.42)
VS (%FM)	20.06 (0.19)	1.56 (0.19)
VS/TS (%)	92.21 (0.54)	79.14 (4.23)
pH	4.80 (0.12)	7.36 (0.06)
TCOD (g/L)	248.2 (18)	2.2 (0.1)
Crude fat (mg/g TS)	283 (13)	–
Cellulose (%TS)	4.30 (0.3)	–
Hemi-cellulose (%TS)	10.05 (0.9)	–
Lignin (%TS)	2.19 (0.2)	–
C (%TS)	48.24 (0.17)	–
H (%TS)	6.90 (0.16)	–
O (%TS)	34.13 (0.31)	–
N (%TS)	2.50 (0.11)	–
S (%TS)	0.44 (0.02)	–
C/N	19.3	–
Fe (mg/kg TS)	230.7 (14.7)	2056.4 (138)
Co (mg/kg TS)	0.38 (0.07)	3.0 (0.27)
Ni (mg/kg TS)	6.72 (0.85)	63.7 (3.9)
Se (mg/kg TS)	0.6 (0.2)	4.3 (1.1)

Values are expressed as mean and figures in parentheses are standard deviations ($n = 3$), FM: fresh matter, TS: total solids.

The background concentration of Fe, Co, Ni, and Se in the FW is very low.

The TEs added in this study were Fe (5.0 mg L^{-1}), Co (1.0 mg L^{-1}), Ni (1.0 mg L^{-1}), and Se (0.2 mg L^{-1}), and these TEs were prepared as $FeCl_2 \cdot 4H_2O$, $CoCl_2 \cdot 6H_2O$, $NiCl_2 \cdot 6H_2O$, and $Na_2SeO_4 \cdot 10H_20$, respectively. The addition methods at different feeding OLRs and digesters are shown in Table 2. The supplementation concentrations were chosen based on the results of previous reports: Fe: 5.0–100 mg L^{-1}, Co: 1.0–2.0 mg L^{-1}, Ni: 1.0–10 mg L^{-1}, and Se: 0.2 mg L^{-1} (Banks et al., 2012; Qiang et al., 2012; Zhang and Jahng, 2012). These doses were selected to avoid reaching toxic TEs concentrations.

The semi-continuously fed digesters had a capacity of 6.0 L and a working volume of 4.5 L. The digester consisted of a PVC (polyvinyl chloride) tube with gas-tight top and bottom plates. The top plate was fitted with a gas outlet, which was connected with a gas bag. The feeding port was sealed with a rubber bung, and the sealed tube with tube bottom was submerged in the fermentation medium. A stirrer with a stirring speed of 40 rpm was fixed through the sealed tube which was fixed in the middle of the top plate. The digestion temperature was maintained at (37 ± 1) °C with a temperature controller. The digestate was drawn out through an outlet port at the bottom of the digester wall, and the raw material was fed into a digester via the feeding port once a day. The produced gas was collected in a gas-tight aluminum bag, and the volume was measured with a wet-type precision gas meter (LML-1, Changchun Qichelvqingqi Co., Ltd., China). The measured gas volume is corrected to value at standard temperature and pressure (0 °C, 101.325 kPa). The experiment was carried out in triplicate.

2.2. Experimental procedure

Two pairs of experimental-scale anaerobic digesters with an active volume of 4.5 L were used in this experiment. The hydraulic retention time (HRT) of all digesters was maintained at 40 d, and the different OLRs were established based on the operation periods shown in Table 2. The first pair of digesters (R1) was used as the control treatment. TEs were not added to R1 [TEs (−)] throughout the experiment. The second pair of digesters (R2) [TEs (+)] was supplemented with different kinds of trace elements (TEs) based on the designed strategies. The digestates were withdrawn daily, and an equivalent quantity of diluted substrate was added to the digesters to maintain a constant volume for all the digesters. All

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