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Transition of municipal sludge anaerobic digestion from mesophilic to thermophilic and long-term performance evaluation

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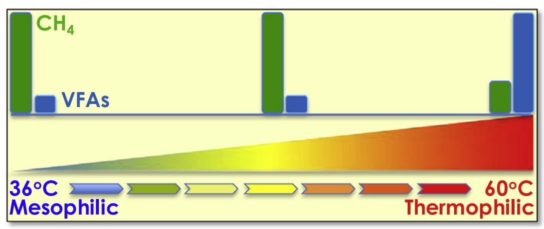
HIGHLIGHTS

- Transition from 36 to 53.3 °C digestion at a rate of 3 °C/day was successful, stable.
- Operation at 60 °C led to relatively stable gas production but high levels of VFAs.
- Methane production at 60 °C was lower than at mesophilic conditions (36 °C).
- For high performance of municipal CSTR digesters, temperature should be below 60 °C.

GRAPHICAL ABSTRACT



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ABSTRACT

Strategies for the transition of municipal sludge anaerobic digestion from mesophilic to thermophilic were assessed and the long-term stability and performance of thermophilic digesters operated at a solids retention time of 30 days were evaluated. Transition from 36 °C to 53.3 °C at a rate of 3 °C/day resulted in fluctuation of the daily gas and volatile fatty acids (VFAs) production. Steady-state was reached within 35 days from the onset of temperature increase. Transitions from either 36 or 53.3 °C to 60 °C resulted in relatively stable daily gas production, but VFAs remained at very high levels (in excess of 5000 mg COD/L) and methane production was lower than that of the mesophilic reactor. It was concluded that in order to achieve high VS and COD destruction and methane production, the temperature of continuous-flow, suspended growth digesters fed with mixed municipal sludge should be kept below 60 °C.

1. Introduction

Anaerobic digestion has long been used as the main sludge stabilization process in municipal treatment plants (Tezel et al., 2011; Tchobanoglous et al., 2014). Most municipal digesters operate at mesophilic temperatures (35 to 37 °C). However, thermophilic digestion above 50 °C has been gaining popularity, primarily because it achieves a higher extent of pathogen reduction, resulting in Class A biosolids, and secondarily because it exhibits faster kinetics. The latter results in higher solids destruction and biogas production compared to mesophilic digestion for the same solids retention time (SRT), or the flexibility to achieve a desired extent of solids destruction while operating at a lower SRT value. Possible disadvantages of thermophilic digestion may include odor, reduced dewaterability of the digested sludge, and higher heating requirement, which may not be compensated for by higher biogas production as compared to mesophilic digestion.

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Conversion from mesophilic to thermophilic digestion has been practiced at both laboratory- and full-scale levels. Two strategies for the transition from mesophilic to thermophilic digestion have been tested: (a) one-step temperature increase in laboratory scale upflow anaerobic sludge blanket (UASB) reactors (Fang and Lau, 1996; Syutsubo et al., 1997; van Lier et al., 1992) and in continuous-flow stirred tank reactors (CSTR) (Bouskova et al., 2005); (b) step-wise temperature increase in CSTR (Zabranska et al., 2002; Bouskova et al., 2005; Palatsi et al., 2009). The results of the Bouskova et al. (2005) study, which used a SRT of 20 days and an organic loading rate of 1.38 g VS/L-day while the reactors were fed during the temperature transition period, showed that the one-step temperature increase from 37 to 55 °C resulted in stable operation in 30 days, as opposed to 70 days for the step-wise temperature increase (37, 42, 47, 51, and 55 °C). Palatsi et al. (2009) evaluated two strategies for the transition from mesophilic to thermophilic of a mixture of primary and secondary municipal sludge in CSTR laboratory reactors with a SRT and organic loading rate ranging from 19.6 to 23.4 days and from 1.29 to 1.73 g VS/L-day, respectively. A single temperature change from 35 to 55 °C required about 20 days for the reactor efficiency to fully recover, but resulted in higher transient VFAs production, especially propionic acid, compared to a step-wise temperature increase (35, 43, 50, and 55 °C), which required a longer time to complete the temperature transition. These researchers pointed out that the temperature range between 43 and 50 °C was critical in switching methanogenic activity from mesophilic to thermophilic. Peces et al. (2013) evaluated the response of a mesophilic anaerobic digester fed with municipal sludge to short- and long-term temperature fluctuations. Transition from mesophilic to thermophilic conditions of a laboratory CSTR and exposure at 55 °C for 24 h resulted in an increase in VFAs and a decrease in gas production; reactor recovery was achieved in 22 days and required a non-feeding period.

A one-step temperature increase is not feasible at full-scale digesters because of heating capacity limits. Full-scale testing for the conversion of a mesophilic to thermophilic municipal sludge digester was assessed by Iranpour et al. (2002) using continuous heating at an average temperature rise of 3 °C/day, increasing the digester temperature from approximately 33 to 55 °C, while using a variable sludge feeding rate. This study achieved stable digester operation in less than 30 days. Further operation of the thermophilic digester achieved Class A biosolids and increased VS destruction and gas production. Information relative to the transition from mesophilic to thermophilic digestion for municipal sludge stabilization is very limited, especially for CSTR digesters, under real, full-scale conditions and constraints. In addition, the potential impact of thermophilic digestion on digestate quality has not been sufficiently assessed.

The objective of the work presented here was to assess different conversion strategies for the transition of municipal sludge anaerobic digestion from mesophilic to thermophilic operation, and evaluate long-term stability and performance of thermophilic digesters in terms of solids destruction, gas production/composition, and digestate quality.

2. Methods

2.1. Sludge samples

The study was designed and conducted by taking into account conditions and constraints at the F. Wayne Hill Water Resources Center (WRC), Gwinnett County, GA, USA. This municipal wastewater treatment plant uses activated sludge technology, achieving both N and P removal. It uses mesophilic (98 °F or 36.7 °C) anaerobic digestion for sludge stabilization and biogas production, which is converted to electricity through combined heat and power technology. Primary and thickened waste activated sludge (TWAS) samples were collected at the F. Wayne Hill WRC. The primary sludge was sequentially passed through a 5 × 5 mm square mesh screen, a 2-mm sieve (US Standard No. 10), and finally a 1.4-mm sieve (US Standard No. 14). The TWAS was not further processed. Both sludge samples were stored under refrigeration (4 °C). The following analyses were performed for both sludge samples: pH, total and volatile solids (TS, VS), total and soluble chemical oxygen demand (tCOD and sCOD), VFAs, and ammonia. The water content of the two sludge samples was not affected by screening.

2.2. Ultimate sludge biodegradability

The test was performed using 160-mL glass serum bottles (120 mL liquid volume), sealed with rubber stoppers and flushed with helium gas following previously described procedures (Tezel et al., 2006). Sludge obtained from a F. Wayne Hill WRC mesophilic anaerobic digester was anaerobically incubated in the laboratory and severed as inoculum (seed). Then, an aliquot of 75 mL of pre-digested sludge was anaerobically transferred to each bottle and 18 mL of media were then added. The media contained (in g/L): K_2HPO_4, 0.9; KH_2PO_4, 0.5; NH_4Cl, 0.5; $CaCl_2{\cdot}2H_2O$, 0.10; $MgCl_2{\cdot}6H_2O$, 0.20; $FeCl_2{\cdot}4H_2O$, 0.10; $NaHCO_3$, 6.7. Also, 10 ml/L each of vitamin and trace metal stock solutions were added to the media (Beydilli and Pavlostathis, 2005). A total of five series in triplicate (5 × 3 = 15 bottles in total) were set up as follows. One series did not receive any sludge and served as the seed blank. Another series was amended with a mix of dextrin/peptone (800/400 mg/L) and served as a check of seed activity (reference series). Three more series were prepared with primary sludge, TWAS, and a mixture of primary sludge/TWAS, respectively. Primary sludge and TWAS were tested at a sample VS loading equal to 3 g/L. Combined primary and TWAS were tested at a total VS loading of 3 g/L and a primary/TWAS TS ratio of 20/80% as practiced at the F. Wayne Hill WRC. Incubation was carried out in the dark at 35 °C and the bottles were shaken manually once a day. Throughout the incubation period, total gas volume and composition (CH_4 and CO_2) were measured frequently. At the end of the incubation, pH, TS, VS, tCOD, sCOD, VFAs and ammonia were measured. The biodegradability test was carried out for 121 days, at which time all gas production had leveled off.

2.3. Digesters set up and operation

All digesters used in this study were made of wide-mouth Pyrex reactors with a water jacket, and their temperature was controlled with water recirculation using heated water-circulating baths. The digesters were housed in a 22–24 °C room and their contents were mechanically mixed at 90 rpm using a shaft magnetically coupled to an external, variable-speed electric drive. Gas produced was collected in graduated burettes by displacement of an acidified brine solution (10% NaCl w/v and 2% H_2SO_4 v/v) and measured after equilibration to atmospheric pressure. Gas data reported here are either at 22 °C and 1 atm or at standard temperature and pressure (STP; 0 °C and 1 atm).

2.3.1. Mesophilic operation (36 °C)

Two digesters (R1 and R2) were set up and operated at 36 °C and a SRT of 30 days (close to the SRT at the plant). The total digester volume was equal to 4 L with a liquid working volume equal to 3 L. Both digesters were started with 3 L mixed liquor obtained from a F. Wayne Hill WRC mesophilic anaerobic digester. The feed for both digesters was primary/TWAS sludge mixture (20/80% on TS basis), which was kept under refrigeration (4 °C). The combined