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Pre-treatment mechanisms during thermophilic–mesophilic temperature phased anaerobic digestion of primary sludge

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ABSTRACT

Pre-treatment is used extensively to improve degradability and hydrolysis rate of material being fed into digesters. One emerging process is temperature phased anaerobic digestion (TPAD), which applies a short (2 day) 50–70 °C pre-treatment step prior to 35 °C digestion in the main stage (10–20 days). In this study, we evaluated a thermophilic–mesophilic TPAD against a mesophilic–mesophilic TPAD treating primary sludge. Thermophilic–mesophilic TPAD achieved 54% VS destruction compared to 44% in mesophilic–mesophilic TPAD, with a 25% parallel increase in methane production. Measurements of soluble COD and NH_4^+-N showed increased hydrolysis extent during thermophilic pre-treatment. Model based analysis indicated the improved performance was due to an increased hydrolysis coefficient rather than an increased inherent degradability, suggesting while TPAD is suitable as an intensification process, a larger main digester could achieve similar impact.

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1. Introduction

Waste organic solids are widely produced by domestic and industrial wastewater treatment plants. Anaerobic digestion is a common stabilisation method for treating these solids, which is environmentally beneficial due to production of renewable energy. However, degradability of the feed material needs to be relatively high, to allow good solids destruction, provide gas for heating and mixing, and prevent washout of methanogens. Degradability is particularly poor in long-sludge age activated sludge systems (Gossett and Belser, 1982). Many long-sludge age systems are also smaller scale (<5 dry tonnes solids produced per day), where high-capital options to enhance degradability, such as sonication or thermal hydrolysis are not available (Barr et al., 2008). To address these limitations in smaller plants, an anaerobic option should (Batstone et al., 2008a):

(a) Improve biogas production to offset energy demand
(b) Increase solids destruction to reduce the volume of sludge requiring ultimate disposal
(c) Increase hydrolysis rates to allow reduced digester size and capital cost and
(d) Achieve pathogen free stabilised solids to expand reuse options.

Temperature phased anaerobic digestion (TPAD) may allow enhanced degradability and biogas production, as well as pathogen destruction, at a relatively low capital cost. TPAD consists of a pre-treatment stage operated under thermophilic temperature (50–70 °C) and short hydraulic retention times (HRT), followed by a main stage operated at lower mesophilic temperature with a longer retention time. Pathogen destruction and hydrolytic and acidogenic conditions can be further optimised in the pre-treatment process. In the following main

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stage, a longer retention time and a neutral pH favour methanogenesis for maximum conversion of organic components to methane.

There have been a number of studies evaluating TPAD systems. Han et al. (1997) tested the effect of different solids retention times for TPAD system (55 °C and 35 °C) compared with conventional single-stage mesophilic (35 °C) digestion on primary sludge and waste activated sludge. They showed that the optimal solids retention time of across both stages of a TPAD system ranged from 11 to 17 days, with volatile solids (VS) destruction up to double in TPAD system compared to single-stage anaerobic digestion. Skiadas et al. (2005) found a VS destruction with TPAD system (70 °C, 2 day HRT and 55 °C) of 55% and 43% for primary and secondary sludge respectively, higher than 43% and 6% achieved in the single-stage thermophilic (55 °C) anaerobic digestion. Watts et al. (2006) reported that lower thermophilic temperatures (47 °C and 54 °C, 2 day HRT) treating waste activated sludge did not offer higher VS destruction over single-stage mesophilic (37 °C) anaerobic digestion. When the thermophilic temperature was increased to 60 °C, VS destruction was improved to 35%, compared with 24% in single-stage mesophilic anaerobic digestion. They also observed increased gas production consistent with the increased VS destruction.

These studies indicate enhanced treatment performance for TPAD systems as compared to single-stage thermophilic or mesophilic systems. However, rigorous analysis is missing, as there is no direct parallel comparison of mesophilic–mesophilic and thermophilic–mesophilic TPAD. There is also little analysis of which conditions (temperature and pH) can optimise eventual hydrolytic conversion. Finally, it has not been established whether enhanced performance is due to increased hydrolysis in the pre-treatment stage, increased overall degradability, or a conditioning process (such as a physical breakdown of sludge similar to that achieved during thermal hydrolysis and sonication), that allows better performance in the main stage. This paper addresses these limitations on a particular feed (primary sludge) by operating parallel thermophilic–mesophilic and mesophilic–mesophilic TPAD systems, and detailed analysis of the pre-treatment process.

2. Materials and methods

2.1. Substrate

The substrate used in this study was primary sludge collected from a large wastewater treatment plant in Brisbane, Australia. The feed was screened with a 3 mm sieve and diluted with tap water to a total solids (TS) concentration of 2–3%. Feed batches were prepared at intervals of 1–2 months and stored at below 4 °C. Regular analysis was performed to determine the characteristics and consistency of the feed material. The average characteristics of the primary sludge feed are shown in Table 1.

Table 1 – Characteristics of the primary sludge used in this study.

Measure	Primary sludge
TS ($g\,L^{-1}$)	26.9 ± 2.9[a]
VS ($g\,L^{-1}$)	20.7 ± 2.0
pH	5–6.5
COD ($g\,L^{-1}$)	30.2 ± 3.2
VFA ($g\,COD\,L^{-1}$)	0.6 ± 0.2
TKN ($g\,N\,L^{-1}$)	1.3 ± 0.6
NH_4^+-N ($g\,L^{-1}$)	0.09 ± 0.02

a Indicates standard deviation across 5 different feed materials used in the study over 6 months.

2.2. Laboratory scale reactor systems

Two identical TPAD systems, as shown in Fig. 1 were used throughout the study. Each system contained a 0.6L reactor (HRT 2 days) for pre-treatment and a 4.0L reactor (HRT 13–14 days approx) as main methanogenic stage. The thermophilic pre-treatment (TP) system and mesophilic pre-treatment (MP) system were operated identically, except for the pre-treatment stage, which was either 50–65 °C (TP1), or 35 °C (MP1). The temperature in the pre-treatment stages was maintained with temperature controlled water jackets, while temperature in the main methanogenic stages was maintained using submersed electrical heating elements. All reactors were continually mixed using magnetic stirrer bars. Gas production volumes and pH were recorded from each reactor and recorded online by a process logic control system.

2.3. Start-up and operation

Each reactor was inoculated from a full-scale anaerobic digester (35 ± 1 °C) in Brisbane, Australia. Reactors were fed at intervals of 4 hours (6 times daily). During feed events, approximately 50 mL of feed was pumped through the system simultaneously using multi-head peristaltic pumps located between the feed reservoirs and pre-treatment stages; pre-treatment stages and methanogenic stages; and methanogenic stages and the waste effluent drums.

The systems were operated for over 6 months. During this time the temperature of TP1 was altered to create different operating periods:

- Period 1: 50 °C (117 days)
- Period 2: 60 °C (20 days)
- Period 3: 65 °C (32 days)
- Period 4: 65 °C, pH 4.5 by dosing of 1 M HCl (14 days).

The TP system had been operated for 64 days before the MP system commenced operation. The temperature of MP1, TP2 and MP2 were held constant at 35 °C during all periods. After Period 4 the acid dosing was stopped and the pH in TP1 returned to its natural level of 6.8. Only data from Day 75 was used in comparative analysis (i.e., after stabilisation of both digesters).

2.4. Analysis

Gas production was measured using tipping bucket gas meters and continuously logged. Gas meters were regularly recalibrated and switched between reactors to prevent

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