Comparison of mesophilic and thermophilic anaerobic digestion of food waste

C. Yirong, C. J. Banks and S. Heaven

Faculty of Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ, UK (E-mail: *cy1g09@soton.ac.uk*)

Abstract
Thermophilic and mesophilic anaerobic digestion of food waste gave similar specific methane yields when operated at an organic loading rate of 2 g VS l^{-1} day^{-1}, which were equal to approximately 70% of the theoretical value based on the Buswell equation. Mesophilic digestion provided better stability as the thermophilic system showed an accumulation of VFA and symptoms of failure when the ammonia concentration reached 3500 mg l^{-1}. It was possible to partially offset failure in the thermophilic system by additional TE supplementation, but this did not prevent a continuing increase in VFA concentration.

Keywords
Food waste; specific methane yield; ammonia; trace elements; volatile fatty acids

INTRODUCTION

Anaerobic digestion is a promising technology for treating domestic food waste as it allows recovery of its energy value in a more effective manner than thermal methods. Likewise the process is conservative with regard to nutrients, and the digestate produced is suitable for use as a bio-fertiliser. Because of the high energy value of the waste and its relatively high volatile solids content both mesophilic and thermophilic digestion could be considered. Thermophilic digestion processes potentially allow higher loadings with reduced hydraulic retention times, higher conversion efficiencies and pathogen disinfection. Mesophilic anaerobic digestion on the other hand may be more stable and less at risk from ammonia nitrogen toxicity (Batstone and Jensen, 2011), and requires less process heat. It is clear, however, that food waste as an AD substrate can lead to the accumulation of volatile fatty acids (VFA) (Banks *et al.*, 2008; Neiva Correia *et al.*, 2008; Park *et al.*, 2008; Zhang *et al.*, 2010), which are generally accepted as an indicator of process instability. For substrates with a high nitrogen content such as food waste it has been suggested that the resulting high ammonia concentrations in the digester may lead to toxicity which is seen by VFA accumulation. Ammonia concentrations thought to be toxic have been variously reported e.g. as (mg N l^{-1}) 2,000 (Khanal, 2008); >3,000 (McCarty, 1964); 4,000 (Angelidaki and Ahring, 1994) and 5,000 (Borja *et al.*, 1996). It is also known that higher temperatures lead to more serious toxicity at the same pH (Ahring *et al.*, 2003), as a result of the shifting of the ammonium/ammonia equilibrium towards the more toxic ammonia state. More recently, food waste digesters have been shown to operate with good gas production and low VFA concentrations at ammonia concentrations in excess of 6000 mg l^{-1}. These digesters have been shown to have a predominantly hydrogenotrophic methanogenic population, and a mechanism by which trace element addition can prevent VFA accumulation at these high ammonia concentrations in mesophilic digesters has been reported (Banks et al., 2012). The research reported here compares both mesophilic and thermophilic digestion of source segregated food waste, and in particular the response to ammonia toxicity.

METHODS

Source segregated domestic food waste was taken from a collection round in Eastleigh, Hampshire, UK. It was manually sorted to remove contaminants and homogenised using a macerating grinder, and stored at -20^{o}C until required, at which time batches were thawed and stored at 4^{o}C for no more than one week. The digesters used were of a continuously-stirred tank reactor (CSTR) design and had

a 4-litre working volume. Temperature was controlled at 35 and 55 ^{o}C for mesophilic and thermophilic trials, respectively. The digesters were seeded with mesophilic digestate from Millbrook Wastewater Treatment Plant, Southampton, UK. For thermophilic trials (thermo-AD) the inoculum was acclimatised by sharply increasing the temperature to 55 ^{o}C and stopping the feed for 7 days, followed by a gradual increase in organic loading rate (OLR) from 0.5 to 2.0 g volatile solids (VS) l^{-1} day^{-1} over 40 days. The OLR on the mesophilic digesters (meso-AD) was 2 g VS l^{-1} day^{-1} from day 1.

Experimental design. The digesters were operated in semi-continuous mode by adding food waste once daily throughout the experimental period and removing digestate to maintain a constant volume. Both sets of digesters were supplemented with trace elements (TE) and received an initial addition of 1 ml l^{-1} of a solution containing (g l^{-1}): Cobalt (Co) 1.0, Nickel (Ni) 1.0, Molybdenum (Mo) 0.2, Selenium (Se) 0.2, Tungsten (W) 0.2. They were then supplemented to maintain this initial concentration by proportional dosing of 1 ml of this solution for every kg of food waste fed.

Analytical Methods. Total solids (TS) and VS were measured using Standard Method 2540 G (APHA, 2005). pH was measured with a combination glass electrode calibrated in buffers at pH 4, 7 and 9. Alkalinity was measured by titration with 0.25N H_2SO_4 to endpoints of pH 5.75 and 4.3, allowing calculation of total (TA), partial (PA) and intermediate alkalinity (IA) (Ripley *et al.*, 1986). . Total Kjeldahl Nitrogen (TKN) was determined using a Kjeltech block digester and ammonia by steam distillation unit according to the manufacturer's instructions (Foss Ltd, Warrington, UK). Volatile fatty acids (VFA) were quantified in a Shimadzu GC-2010 gas chromatograph (Shimadzu, Milton Keynes, UK), using a flame ionization detector and a capillary column type SGE BP-21. Biogas composition (CH_4 and CO_2) was determined using a Varian star 3400 CX Gas Chromatograph, and calibrated with 65.12% (v/v) CH_4 and 34.88% (v/v) CO_2. Elemental analysis was done through the automatic analyser (FlashEA 1112 Elemental Analyzer, Thermo Finnigan, Italy). Biogas was measured using tipping-bucket gas counters with continuous data logging (Walker *et al.*, 2009) and all gas volumes reported are corrected to standard temperature and pressure of 0^{o}C, 101.325 kPa. Theoretical biogas production was calculated using the Buswell equation (Buswell and Mueller, 1952).

RESULTS AND DISCUSSION

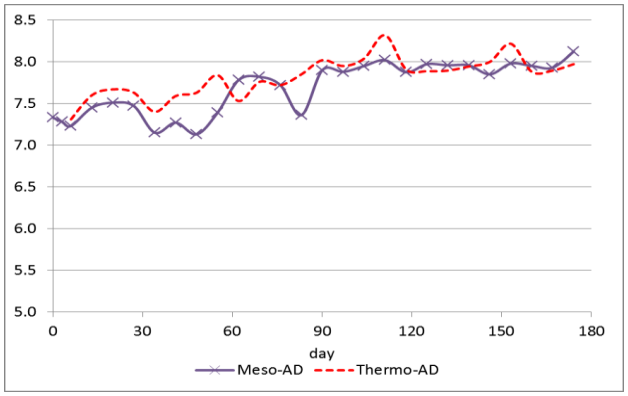
Food waste characteristics. The food waste had a TS of 23.9%, VS 21.6%, TKN 30.9 g N kg^{-1} TS. The compositions of carbohydrates, proteins and lipids were 525, 213 and 151 g kg^{-1} VS, respectively. COD was 267 g kg^{-1} fresh matter. The elemental composition on a % TS basis was Carbon 51.1, Hydrogen 6.41, Oxygen, 32.5 and Nitrogen 3.1, giving a calculated theoretical specific methane yield of 0.66 l CH_4 g VS^{-1} with a biogas methane content of 58%.

Digester performance

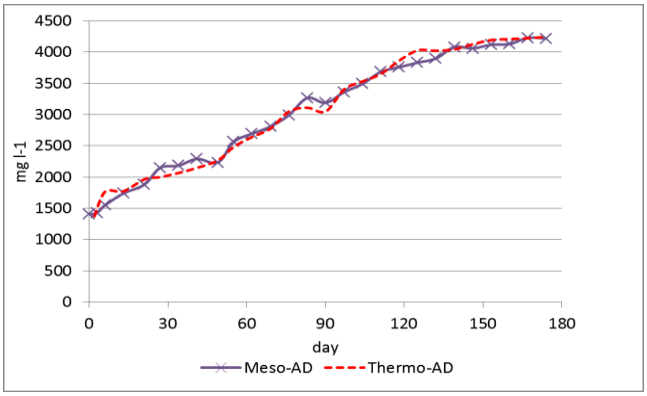
The digesters were operated continuously for 177 days (Figure 1). Both the meso-AD and thermo-AD required some acclimatisation. The meso-AD showed a period of higher VFA, lower biogas production and higher IA/PA ratio between days 40 - 70 (Figure 1h, f and c); while the thermo-AD showed some initial instability up to day 25 (Figure 1c, d, f and h) and was operating stably by the time the full loading of 2 g VS l^{-1} day^{-1} was applied on day 40. Throughout the remaining operational period the meso-AD showed: a gradual increase in pH and alkalinity, resulting from the increasing ammonia in the digester; a decreasing IA/PA ratio; a stable methane concentration around 58%; low VFA concentrations; and a specific methane yield of 0.47 l CH_4 g^{-1} VS.

The thermo-AD showed stable operation with a specific methane yield of 0.45 l CH_4 g^{-1} VS, and VFA concentrations >1000 mg l^{-1} until around day 100, after which time there was clear increase in VFA concentrations and in particular a steady accumulation of propionic acid. On day 112 there was a very rapid increase in acetic acid concentration accompanied by a sharp fall in biogas production: at this point a one-off TE supplementation was given to raise the concentration in the

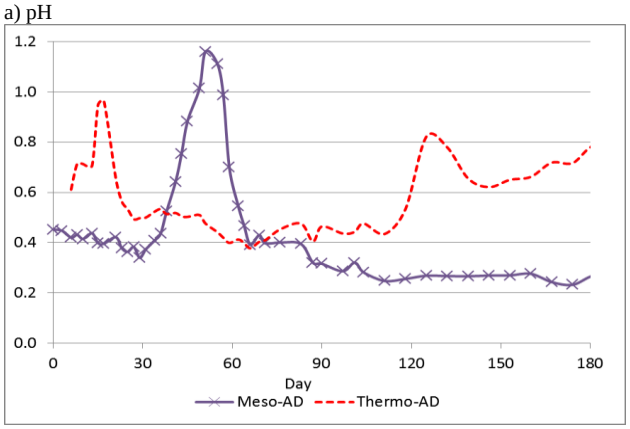
digester and the regular TE dose was also increased to 4 times that previously applied, in an attempt at recovery. By day 128 the acetic acid concentration began to fall followed by reductions in n-butyric, valeric and hexanoic acids; but propionic, iso-butyric and iso-valeric acids continued to accumulate (Figure 1h).



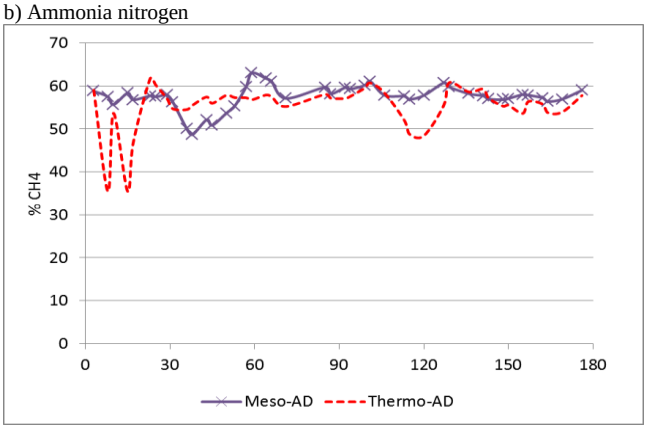
a) pH



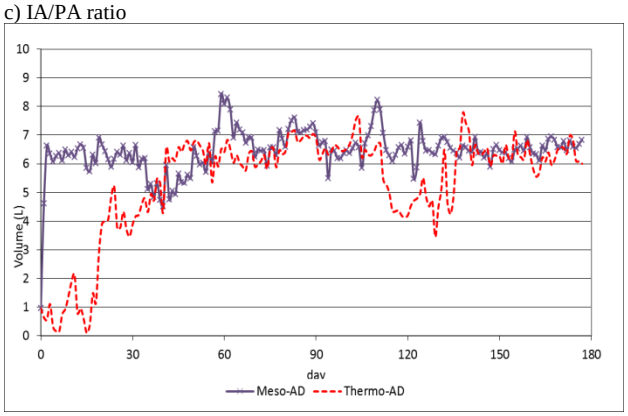
b) Ammonia nitrogen



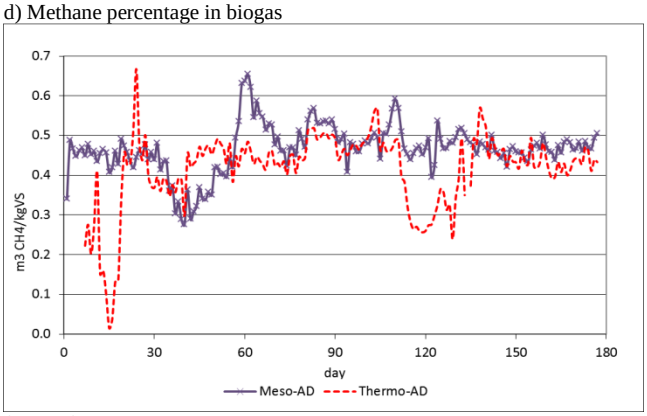
c) IA/PA ratio



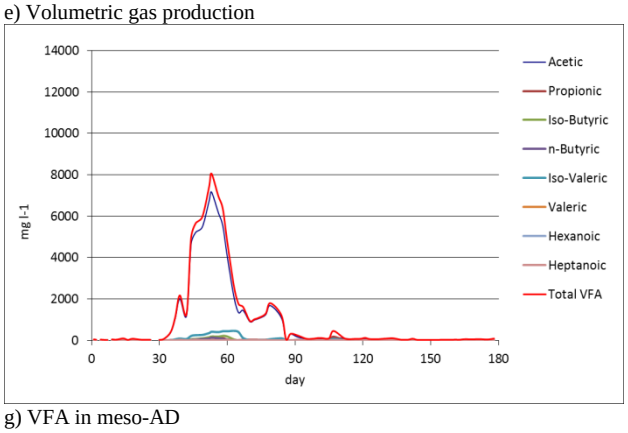
d) Methane percentage in biogas



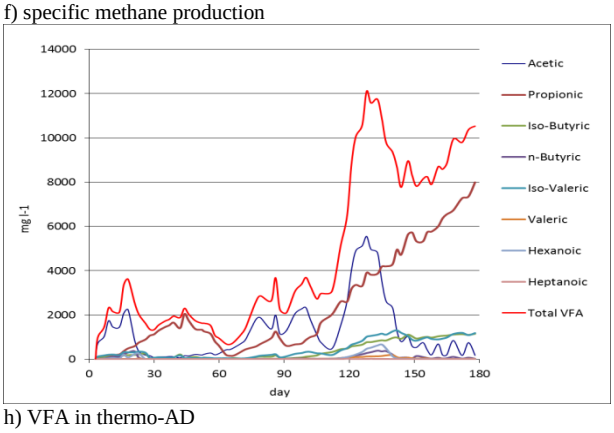
e) Volumetric gas production



f) specific methane production



g) VFA in meso-AD



h) VFA in thermo-AD

Figure 1 Digestion parameters during experimental run

Difficulties in operating at thermophilic temperatures could be attributed to a combination of trace elements deficiency and ammonia toxicity. Uemura (2010) and Takashima *et al.* (2011) showed that thermophilic systems required more trace elements than mesophilic ones, and the current results support this as there was some response to the increased supplementation. Accumulation of VFA is a known consequence of ammonia toxicity, and at the point this started to occur the ammonia concentration had reached around 3500 mg l^{-1} (Figure 1b and 1g), a similar value to previous reports (McCarty, 1964; Angelidaki and Ahring, 1994; Sung and Liu (2003); Hendriksen and Ahring (1991). The increased trace element dosage, however, was not effective in resolving this problem.

CONCLUSIONS

Thermo-AD of food waste gave a similar specific methane yield to meso-AD when operated at an OLR of 2 g VS l^{-1} day^{-1}, equal to approximately 70% of the theoretical value based on the Buswell equation. The meso-AD was more stable than Thermo-AD, which showed an accumulation of VFA and symptoms of failure when the ammonia concentration reached 3500 mg l^{-1}. It was possible to partially offset this by additional TE supplementation, but this did not prevent the continuing increase in VFA concentration.

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