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Ammonia removal in food waste anaerobic digestion using a side-stream stripping process

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HIGHLIGHTS

- Biogas side-stream stripping reduced ammonia concentrations to below toxic level.
- Improved organic nitrogen destruction by thermally-mediated alkaline hydrolysis.
- Methanogenic population able to adapt to different ammonia concentrations.
- Reduced ammonia raises potential for better digestate utilisation.
- Ammonia recovered as value-added product from side-stream process.

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ABSTRACT

Three 35-L anaerobic digesters fed on source segregated food waste were coupled to side-stream ammonia stripping columns and operated semi-continuously over 300 days, with results in terms of performance and stability compared to those of a control digester without stripping. Biogas was used as the stripping medium, and the columns were operated under different conditions of temperature (55, 70, 85 °C), pH (unadjusted and pH 10), and RT (2–5 days). To reduce digester TAN concentrations to a useful level a high temperature ($\geqslant$70 °C) and a pH of 10 were needed; under these conditions 48% of the TAN was removed over a 138-day period without any detrimental effects on digester performance. Other effects of the stripping process were an overall reduction in digestate organic nitrogen-containing fraction compared to the control and a recovery in the acetoclastic pathway when TAN concentration was 1770 ± 20 mg kg^{-1}.

1. Introduction

The source segregation, separate collection and subsequent anaerobic digestion of food waste can help to reduce the organic fraction of municipal solid waste for disposal and, in some cases, help governments to meet the targets of the EU Directive on the landfilling of waste (1999/31/EC). Importantly, it also offers a method of reclaiming potential energy in the waste in the form of a fuel gas, and opens up a route by which nutrients can be recycled back to land. This has advantages even compared to incineration for energy recovery, as the high moisture content of food waste negates much of the energy gain and in thermal processing most nutrients are lost. Digestion may therefore offer a more sustainable route to resource recovery compared to other waste treatment technologies that are less suited to dealing with this high moisture fraction. Anaerobic digestion of food waste is not without difficulties, however, mainly associated with its high protein content. On hydrolysis this releases ammoniacal nitrogen which, although essential for the growth of anaerobic microorganisms, can lead to free ammonia concentrations that are inhibitory to the digestion process. The ammonia inhibits the methanogenic archaea, in particular the acetoclastic methanogens (Kayhanian, 1999; Chen et al., 2008; Liu and Sung, 2002; Prochazka et al., 2012; Angelidaki and Ahring, 1993). The result is operational instability, a decrease in biogas production, and in the worst cases failure of digestion. To some extent these problems have been resolved at mesophilic temperatures through stimulation of the hydrogenotrophic metabolic pathway by the addition of selenium and cobalt, both of which are commonly deficient in food waste (Climenhaga and Banks, 2008). This strategy has allowed stable digestion of food waste at high organic loading rates (OLR) (>5 kg VS m^{-3} day^{-1}) and total ammoniacal nitrogen (TAN) concentrations >6 g l^{-1} (Banks et al., 2012). At temperatures in the thermophilic range the toxic threshold is reduced as the equilibrium moves towards free ammonia, and under these conditions trace element additions have not been successful in overcoming the associated problem of volatile fatty acid (VFA) accumulation

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as the methanogenic/acetogenic syntrophy breaks down (Yirong et al., 2013). Yirong et al. (2013) compared mesophilic and thermophilic digestion of source segregated food waste without water addition into the system and found failure symptoms in the thermophilic system when TAN concentration reached 3.5 g N l^{-1}. To solve these operational problems in thermophilic anaerobic digestion of food waste one approach is to reduce the TAN concentration in the digester by dilution (Neiva Correia et al., 2008) but this has both resource and energy implications. Co-digestion to increase the C/N ratio is also possible, but depends on the availability of a suitable low nitrogen co-substrate. Reducing the ammonia in the digester or its feed are also possible solutions.

The application of ammonia stripping to the feedstock (pre-digestion) has been tested with piggery and poultry wastes (Zhang et al., 2011; Liao et al., 1995; Bonmati and Flotats, 2003; Gangagni Rao et al., 2008). Removal after first stage fermentation has been tested when treating abattoir, municipal and sewage sludge wastes (Resch et al., 2011; Nakashimada et al., 2008; Yabu et al., 2011). A side-stream process has been tested for slaughterhouse wastes after membrane separation at temperatures below 65 °C and pH 8.5–9 with NaOH addition (Siegrist et al., 2005); and for the liquid fraction of chicken manure digestate under 80 °C and a vacuum pressure of 600 mbar without pH adjustment (Belostotskiy et al., 2013). In both cases the free ammonia concentration was maintained below the inhibition threshold. By using these techniques a wider range of high N feedstocks including food waste (domestic and commercial), abattoir waste and some animal manures are candidates for anaerobic digestion as a single substrate in both mesophilic and thermophilic conditions. The side-stream stripping process is particularly attractive as it is a simple 'bolt-on' concept that could be used with existing anaerobic digestion process designs. Additionally, nitrogen can be recovered as ammonium sulphate, an important nitrogen fertiliser source, and the use of nitrogen-reduced digestate allows a higher application rate in nitrogen-vulnerable zones under the Nitrates directive (91/676/EEC).

The aim of the application of side-stream stripping to anaerobic digesters treating food waste was to reduce the TAN concentration to a point where it would be unlikely to inhibit a thermophilic digester, analysing a number of different stripping conditions. It was also considered essential to monitor the digesters over an extended period to assess the long term effect of the stripping process, as the process itself subjects a portion of the digestate to both temperature and pH shock before returning it to the digester, with a potentially detrimental effect on digestion performance. Although the processes being developed in this research are primarily intended for use with thermophilic digestion the experiments used mesophilic conditions as the starting point since these allow operation at a high concentration of ammoniacal N in the digester, as necessary for demonstration of a side-stream process operating at a low bleed rate. The experiments were carried out against control digesters without side-stream interventions and in all cases a standard biogas of 65% CH_4 and 35% CO_2 (v/v) was used in the stripping process.

2. Methods

2.1. Digesters

Four 35-L working volume continuously-stirred tank reactors (CSTR) were used, constructed from PVC pipe sealed at its top and bottom with plates incorporating feed and drainage ports. Temperature was controlled by recirculating water from a thermostatic bath through an internal heating coil to keep the digesters at 36 ± 1 °C. The digesters were sealed from the outside atmosphere by a draught tube through which an offset bar stirrer was inserted to allow low speed mixing at 30 rpm by means of geared motors. Biogas production was measured using continuous gas flow meters (Walker et al., 2009). Gas yield was corrected to standard temperature and pressure (0 °C and 101.325 kPa). Biogas was also collected in a gas-impermeable bag for 1.5-h periods starting 5 h after reactor feeding; this sample was used to determine the biogas composition at least once per fortnight.

2.2. Digester inoculum

Inoculum was taken from digesters that had been acclimated to source segregated household food waste (OLR 2 g VS kg^{-1} day^{-1}) with trace element supplementation. These digesters had shown good performance and stability and had operated for over 4 hydraulic retention times (HRT) before the start of the current trial. The characteristics of the original inoculum used in the experiment are shown in Table 1.

2.3. Food waste

The digesters were fed on source segregated domestic food waste collected commercially by Veolia Environmental Services (UK), from homes in Eastleigh, UK. The waste was collected in biodegradable plastic bags and a representative sample of around 300 kg was taken periodically as required, from the same collection round. The food waste was taken out of the bags, and any obvious non-food contamination removed along with large bones and seeds. The sample was then ground (S52/010 Waste Disposer, IMC Limited, UK) to a homogeneous pulp, well mixed as a single batch and frozen at −18 °C in snap top plastic containers in ~4 kg aliquots. When needed, the feedstock was thawed and stored at 4 °C and used over a short period. The characteristics of the different batches of food waste used in the experiment are shown in Table 1.

2.4. Analytical methods

Total solids (TS) and volatile solids (VS) were measured according to Standard Method 2540 G (APHA, 2005) using an Heraeus Function Line Series oven and a 201/301 Carbolite muffle furnace. pH was determined using a Jenway 3010 meter (Bibby Scientific Ltd, UK) with a combination glass electrode calibrated in buffers at pH 4, 7 and 9.2 (Fisher Scientific, UK). Alkalinity was measured by titration with 0.25 N H_2SO_4 to endpoints of pH 5.75 and 4.3 using an automatic digital titration burette system (SCHOTT titroline easy) to allow calculation of total (TA), partial (PA) and intermediate alkalinity (IA) (Ripley et al., 1986). Total Kjeldahl Nitrogen (TKN) indicates the sum of organic nitrogen (N_{org}) and TAN (ammonia and ammonium). TKN was determined after acid digestion by steam distillation and titration. This used a BÜCHI K-435 Digestion Unit with H_2SO_4 and K_2SO_4 as the reactants and $CuSO_4$ as the catalyst to convert the amino-nitrogen and free ammonia (NH_3) to ammonium (NH_4^+). This was then measured as TAN using a BÜCHI Distillation Unit K-350 with NaOH addition followed by collection of the distillate in boric acid indicator and titration with 0.25 N H_2SO_4. Volatile fatty acid concentrations (VFA) were determined by gas chromatography (Shimadzu GC-2010), with a flame ionization detector and a capillary column (SGE BP-21) and helium as carrier gas. Samples were acidified to 10% using formic acid and measured against mixed standards of 50, 250 and 500 mg l^{-1} of acetic, propionic, iso-butyric, n-butyric, iso-valeric, valeric, hexanoic and heptanoic acids (APHA, 2005). Biogas composition (CH_4 and CO_2) was determined using a Varian star 3400 CX Gas Chromatograph fitted with a packed stainless steel SUPELCO