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Evaluating an anaerobic digestion (AD) feedstock derived from a novel non-source segregated municipal solid waste (MSW) product

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ABSTRACT

In many nations industrial scale AD of non-agricultural waste materials (such as MSW) has not yet reached its full potential, often constrained by the lack of secure, inexpensive, high quality AD feedstocks, and markets for the resulting digestate material. We tested the output material of a high throughput novel industrial process to define its potential as an AD feedstock (based on quality and consistency). This process, designed to circumvent the constraints of source segregation while still generating segregated waste streams, resulted in the production of a temporally homogenous fibrous material with: an average moisture content of 44.2 (±2.33)%; C:N ratio of ~32.9:1 (±3.46:1), C:P ratio of ~228:1 and gross calorific value of 17.4 (±0.29) MJ/kg$_{(DM)}$. This material provided a CH_4 yield of between 201 and 297 m^3 CH_4/tonne$_{(DM)}$ (271–401 m^3 CH_4/tonne$_{(vs)}$) comparable to commonly used AD feedstocks. Material contaminant levels were temporally consistent ($P > 0.05$), (average values being Cd 0.63 (±0.19), Cu 56.3 (±7.45), Cr^{tot} 51.4 (±4.41), Hg < 0.3, Ni 28.9 (±5.17), Pb 79.2 (±23.71), Zn 202 (±44.5), total polyaromatic hydrocarbons (PAH) 2.2 (±0.3), and total polychlorinated biphenyls (PCB) (<0.2) mg/kg$_{(DM)}$). Calculated digestate contaminant levels were below the median contaminant threshold limits for anaerobic digestates of all countries within the European Union i.e. of Cd 3.35, Cu 535, Cr^{tot} 535, Hg 8.15, Ni 185, Pb 397.5, Zn 2100 mg/kg$_{(DM)}$. We suggest that novel high throughput processes that produce high quality AD feedstocks, may have a place in further diversion of waste from landfill.

1. Introduction

Although 84% of MSW is collected globally, only 15% is currently recycled (Zaman, 2016) and, regardless of country income, landfilling is the predominant disposal route (Zaman, 2016). Although the European Directive on Landfill of Waste (European Commission, 1999) has reduced the disposal of biodegradable municipal waste to landfill (Bulkeley et al., 2005; Edwards et al., 2015) a wide variation (5–80%) in diversion rates still exists amongst member states (European Commission, 2015). The European Commission is currently developing a long term vision to address this disparity (European Commission, 2015), however, in countries where diversion of biodegradable waste from landfill has increased from a low baseline such gains have more recently reduced or plateaued. For instance, the UK increased diversion from 11% in 2000–2001 to 43.2% in 2011–2012 (DEFRA, 2012), however, the rate of progress has reduced year on year since 2005 and from 2012 to 2013 the diversion rate only increased by 0.3% (DEFRA, 2013). Often source-segregation is advocated as a 'key to the success' in non-landfill waste management systems (Yang et al., 2011), but, success is determined by the complex interplay of environmental, economic, and social factors (Di Maria et al., 2016; Tavares et al., 2009; Rispo et al., 2015; Bulkeley and Gregson, 2009) interacting within changing governance and political systems (Bulkeley et al., 2005). Interestingly, Rispo et al. (2015) has suggested that source-segregation may be particularly challenging within hard to reach high density urban communities. We suggest that to realise a 'resource efficient, circular economy' where biodegradable waste becomes a valued resource (DEFRA, 2015; European Commission, 2015), novel and diverse approaches to municipal waste management will be essential including where source-separation is not favoured, practicable, or financially viable (DEFRA, 2013).

Biogas production from 'waste products' by Anaerobic Digestion (AD) is often described as an environmentally sympathetic, and economic method of fuel and 'nutrient-rich fertiliser' generation

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(Bolzonella et al., 2006; DEFRA, 2010; Tambone et al., 2010; Di Maria et al., 2013; Massaccesi et al., 2013). AD is, therefore, an important means (Fricke et al., 2005) of addressing the interconnected issues of: sustainable waste management (European Commission, 1999; Edwards et al., 2015); renewable energy provision, and; 'stabilisation of greenhouse gas (GHG) emission rates' (UNFCCC, 1997; Beurskens et al., 2011). However, slow adoption of AD within non-agricultural settings is often attributed to availability of high quality secure feedstocks, and limited potential to develop economically and environmentally sustainable markets or disposal routes for the resulting digestates (Brooks and Maxwell-Jackson, 2012; WRAP, 2013; Bulkeley et al., 2005) which are governed by regulatory requirements at both broad international and specific national levels (Saveyn and Eder, 2014). Critically, a common feature of compliance for primary waste feedstocks is their segregated at source (WRAP, 2011; Saveyn and Eder, 2014). Feedstocks produced from non-source segregated materials may require extensive pre-treatments, produce lower or variable biogas yields, and also require more intensive post treatments of liquids and solids discharged from the reactors (Di Maria et al., 2012); all of which will require additional investment and have higher operational costs.

Since the 1990s there has been increasing interest in development and introduction of industrial scale MSW processing facilities aimed at enhancing the recovery and reuse of high value materials from non-source segregated MSW (e.g. Mechanical Biological Treatment) (Gioannis et al., 2009; Montejo et al., 2013). A number of these processes include stabilisation of biodegradable materials, through composting or AD, as a stage within a sorting and separation process (Fricke et al., 2005) e.g. SORting- DIgestion- SEPeration (SORDISEP) (Torfs et al., 2005). In parallel, in the last 25 years, autoclaving has gained interest as a mechanism for the treatment of clinical solid waste, household waste, and non-source segregated MSW (e.g. DEFRA, 2013; Garcia et al., 2012), and it is thought that this process may be applied further e.g. to the rejected fractions of mechanical biological treatment (MBT) to maximise recycling rates (Garcia et al., 2012). Autoclaving is a hydrothermal high pressure treatment process (from temperatures of 121 °C to 145 °C and pressures of up to 3 Bar) routinely used in the decontamination of infectious lab waste, clinical and dental tools. Autoclaving is less physically aggressive than steam explosion which is typically carried out at higher temperatures (of 160–260 °C) and pressures (of 6.9–48.3 Bar), and which are accompanied by a rapid pressure release (e.g. 20 s duration) which aids material transformation e.g. in wood products (Teghammar et al., 2010; Vochozka et al., 2016).

With regard to treatment of mixed household and MSW, autoclaving has been shown to have the potential to reduce the initial volume of waste (through maceration and compaction; Garcia et al., 2012), which if combined with post autoclave material segregation can divide recyclable materials into separate fractions (i.e. glass, plastic, ferrous metals, non-ferrous metals, textiles), and result in the production of a single unified organic material product (Garcia et al., 2012). To date studies of this treatment method have often been carried out using synthesised waste materials, at relatively small lab, or pilot, scale (Houltman et al., 2016; Papadimitriou et al., 2008; Papadimitriou, 2010). Within this study we use a full capacity industrial scale rotational autoclave (roto-autoclave) process as a model system for the production of an AD feedstock from non-source segregated MSW. The aim of this study was to assess both the quality and consistency of this fibrous material produced in this process: in terms of physical, chemical and biological attributes (Fig. 1), and to compare these with commonly used anaerobic digestion feedstocks, and with existing regulations.

2. Methods

2.1. Processing

The industrial process was run at full capacity utilising local authority derived MSW for 10 consecutive days. Successive non-sorted batches of the MSW (12 × 20 tonne batches in a 24 h period) were treated by roto-autoclaving, at 140 °C for 45 min at a maximum pressure of 3 bar before depressurisation and cooling (20 min). This process was followed by extensive semi-continuous mechanical separation which included an initial finger screen which removed large items (>200 mm), followed by; air separation, magnets, eddy current separators, optical sorters, glass separators, and a manual picking station (to remove further textiles, and large items). This produced 6 distinct waste streams – glass, plastic, ferrous metals, non-ferrous metals, textiles, and a fibrous material (diameter ⩽ 12 mm). A waste stream mass balance was not conducted during this trial as the focus was exclusively on the fibre output.

A composite sampling protocol was carried out based on ASTM D5956-96 (2006) and ASTM D6051-96 (2015) for fibre analysis (rather than using sorting based methods usually applicable to MSW e.g. ASTM D5231-92 (2008)). Samples were obtained at the final point of mechanical separation whereby 8.5 kg of the fibrous material (⩽12 mm) was collected at intervals of 2 h for 24 h (in a large covered receptacle). Each 24 h period was classified as 1 sampling day (there were 10 consecutive sampling days). After the 24 h period, the resulting material (102 kg) was thoroughly mixed and divided using coning and quartering (ISO 23909, 2008) and 25 kg of the resultant homogenised bulk sample was divided into distinct aliquots which were either refrigerated (4 °C), frozen (−80 °C), or dried (at 105 °C) for down-stream analysis (outlined in Sections 2.2–2.6). The storage, preservation and processing times of samples was dictated by the downstream methods used (Sections 2.2–2.6).

2.2. Characterisation

The fibrous material was analysed for Cd, Cr, Cu, Hg, Ni, Pb, Zn (BS EN 15297, 2011), total N, C, O, S, H (BS EN 15104, 2011), calorific value (BS EN 14918, 2009), moisture content (BS EN 15414-3, 2011), total Kjeldahl nitrogen (TKN) using a Gerhardt reflux and distillation system (Gerhardt, Germany; BS EN 16169, 2012), weight loss on ignition at 550 °C (LOI_{550} which is equivalent to VS), total poly-aromatic hydrocarbons (PAH i.e. sum of 16 US Environmental Protection Agency commonly tested PAH; BS EN 15527, 2008), total polychlorinated biphenyls (PCBs) (BS EN 15308, 2008), microbial pathogen indicator organisms i.e. *E. coli* (ISO 11866-2, 2005; using a colony-count technique at 44 °C) and *Salmonella* (ISO 6579, 2002; using the horizontal method), biogas production potential (Sections 2.3 and 2.4), material structure analysis by Environmental scanning electron microscopy (ESEM; Section 2.5), and carbon characterisation by Fourier Transform Infrared spectroscopy (FTIR), and by thermo-gravimetric differential scanning calorimetry (TG-DSC) analysis; Section 2.6.

2.3. AD batch system set up and gas analysis

Samples from each of the 10 sampling days were set up in triplicate, in 120 ml Wheaton serum bottles, using a 3% dry solid content (the liquid component was made up of a 1:1 ratio of deionised water:acclimatised anaerobic sludge inoculum, and the ratio of inoculum to fibrous material (dry mass) was 15:1). Additionally, a triplicate inoculum only blank was used. The inoculum was

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