Biomass and Bioenergy 86 (2016) 146–155

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: http://www.elsevier.com/locate/biombioe

Research paper

The ability of macroalgae to stabilise and optimise the anaerobic digestion of household food waste

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ARTICLE INFO

Article history:
Received 9 June 2014
Received in revised form
19 October 2015
Accepted 31 January 2016
Available online 12 February 2016

Keywords:
Food waste
Seaweed
Co-digestion
Trace elements
Biomethane potential
Heavy metals

ABSTRACT

This study investigated the potential of seaweed waste (SW) as a sustainable feedstock for anaerobic co-digestion with food waste (FW). The study was conducted at laboratory scale using a batch test approach run over 34 days. Methane (CH_4) potential assays were conducted at the following FW to SW dry mass ratios: 100:0, 90:10, 75:25, 50:50 and 0:100. Results indicated that anaerobic co-digestion of FW and SW at a mixture ratio of 90:10 produced the highest methane yield (252 $cm^3\ g^{-1}$ of volatile solids (VS)), rates of reaction (0.08 d^{-1}) and resulted in a better stability of the process. Predictions based on the Buswell formula suggested that all reactors were performing below the theoretical (maximum) with a greater disparity at increasing levels of seaweed in the feed, likely due to high levels of sulphur in the SW (1.73% mass fraction). The analysis of heavy metals in SW and final digestate indicated that using SW for anaerobic co-digestion with FW enhanced the process by providing trace nutrients without impacting the heavy metal content of the digestate. The analysis of carbon (C) and nitrogen (N) indicated that by using SW for co-digestion with FW, C:N optimal mass ratios were achieved. It was concluded that the addition of SW for anaerobic co-digestion of FW can be used to accelerate the bioenergy production from FW. An additional benefit will be the abatement of the negative impacts of SW in coastal areas, making the overall process more sustainable.

1. Introduction

Current European Union directives driving the diversion of organic wastes from landfill [1] and are set to ensure 20% of energy consumption is from renewable sources, 10% of this coming from biofuels [2]. Anaerobic digestion is a technology which combines both waste management and energy recovery [3]. The anaerobic digestion process consists of three steps: (i) a hydrolysis step in which organic compounds, such as polysaccharides, proteins, and fats are hydrolysed by extracellular enzymes; (ii) an acidification step in which the products of the hydrolysis are converted into H_2, formate, acetate and higher molecular weight volatile fatty acids; and (iii) a third step in which biogas, a mixture of carbon dioxide (CO_2) and methane (CH_4), is produced from H_2, formate and acetate [3].

Anaerobic digestion of food waste has received increasing attention in recent years for its biomethane potential (BMP) [4]. Substantial growth of industrial scale food waste digesters has been observed across the United Kingdom, with over 150 anaerobic digestion sites being built in the last decade to take food waste as either a part or full feedstock [5]. Despite the increased interest and high CH_4 output from food waste, process stability and optimisation is still required [6], where a stable reactor is one free from interferences which ultimately inhibit overall methane production [7]. Recent studies have identified that food waste alone lacks essential trace elements which if neglected can lead to reactor failure [8]. It has been reported that through trace nutrient addition CH_4 production alone can be increased by up to 67% [9]. Another key factor to ensure a balanced and stable reactor is carbon to nitrogen, *i.e.*, C:N mass ratio of the feed. Co-digesting food waste with other waste streams may help to optimise the C:N mass ratio [10] and provide a more balanced feedstock for process stability. Due to the large amounts of CO_2 fixating macroalgae (seaweed) commonly found washed up along UK beaches, it is suggested that co-digestion of seaweed waste, as a sustainable seasonal source of feedstock, with food waste will increase biogas production and reduce negative impacts to environmental and human health. In fact, if seaweed waste is left unattended they can become both

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http://dx.doi.org/10.1016/j.biombioe.2016.01.021
0961-9534/

unsightly to tourists and a biohazard [11]. The last decade has seen a significant increase in 'Green tides', a possible result of eutrophication, which is leading to increased concern of large masses of green seaweed being deposited along coastlines [12]. Whilst the problem persists, appropriate waste management for the seaweed waste is required. For Scotland, an area surrounded by large coastal areas seaweed is an abundant resource where traditional practices have included the use of seaweed for land fertilisation [13].

The anaerobic digestion of seaweed is an emerging area of research [14], and it has been recently reported that large scale macroalgal cultivation offers favourable energy returns compared to other biofuel processes [15]. Macroalgae do however still maintain lower yields of methane per mass of feedstock added to that of terrestrial crops. BMP studies show 132–340 cm^3 g^{-1} VS macroalgae [16] compared to 390–530 cm^3 g^{-1} VS for terrestrial crops [17]. Low methane yields could be due to: (i) unbalanced C:N ratios, which according to the literature could be amended by co-digesting macroalgae with N rich compounds [18]; (ii) inhibitory effect of high levels of sodium [19]; (iii) inhibitory effect of heavy metals, which may be present mainly due to the ability of macroalgae to bioaccumulate them [20]. Further considerations are required if macroalgae is used as a feedstock for anaerobic digestion: (i) high levels of sulphur in macroalgae may result in high concentration levels of hydrogen sulphide (H_2S) in the biogas produced, which may make methane unsuitable for energy recovery without specific treatment [21]; (ii) high levels of heavy metals in macroalgae may render final digestate quality unsatisfactory, according to the British Standards Institute (BSI) standard PAS 110 [22].

The aim of this work was to assess the potential of anaerobic co-digestion of food waste with seaweed waste in an attempt to overcome the challenges of anaerobic digestion of the individual feedstocks presented. For this purpose experimental research was conducted at laboratory scale, which simulated the anaerobic co-digestion of food waste with seaweed waste at a range of food waste to seaweed waste (FW:SW) ratios. The specific objectives were to: (i) assess the effect of adding seaweed waste as a co-substrate in the anaerobic digestion of food waste on the BMP; (ii) investigate what influence seaweed waste has on the reaction kinetics of the anaerobic digestion of the mixture compared to that of food waste alone; and (iii) investigate the impact heavy metals and sulphur content in both food waste and seaweed waste may have on the use of the digestate produced. A technical and economic study of the process was outside the scope of this study.

2. Materials and methods

Five experimental conditions were tested in triplicate using laboratory-scale reactors. The standard anaerobic digestion reactors comprised two substrates (food waste, FW; seaweed waste, SW). Control reactors consisted of only FW or SW. Blank reactors consisted of digestate and de-ionised water to ensure equal headspace. The logistic approach to pinpoint the effect of adding alternative waste streams as co-substrates to FW anaerobic digestion for maximum CH_4 production was to investigate the co-digestion of FW:SW at the dry mass ratios: 100:0; 90:10; 75:25; 50:50 and 0:100. For every mixture ratio of FW and SW, reactors were run simultaneously in triplicates to determine the BMP. Three additional reactors for every mixture ratio of FW and SW were also set-up for destructive testing at days 0, 7 and 15. Control and blank reactors were also run simultaneously in triplicate.

2.1. Substrates

A surrogate FW mixture representing the top ten food and drink waste streams at stated proportions of avoidable (fresh food, *i.e.*, fruit/vegetable flesh) and unavoidable (unconsumed parts of food, *i.e.*, peelings or stalks) waste in Scotland [23] was used. The FW was prepared by blending in a food processor vegetables, fruit, yoghurt and milk, bread and cake, egg shells, tea and coffee grounds and soft drinks (d.w. basis) according to Table 1.

Seaweed was collected in August 2013 from three locations near Edinburgh (UK): (a) North Berwick beach, West Bay Scotland where the estuary of the Firth of Forth meets the North Sea [56.0° N, −2.7° W]; (b) Dunbar beach, North Sea coast [41.6° N, −87.1° W]; and (c) Portobello beach, Firth of Forth [55.9° N, −3.1° W]. Seaweed types were classified according to Wells [24].

The mass fractions of the mixture of dry alga used in this study are indicated after each species: *Fucus serratus* (41%), *Fucus vesiculosus* (12%), *Enteromorpha* (7%), *Ulva Lactua* (17%), *Palmira Palmata* (1%) and *Laminaria Digita* (22%) were washed with tap water, air dried for 72 h, milled to less than 2 mm in particle size (Mill grinder, Retsch, ZM200) and frozen as per [25]. The rationale for this was in the event of scalable anaerobic digestion of seaweed, processing a representative waste mixture of seaweed from the surrounding beaches in the region would prevent the additional cost associated to separation of different species.

2.2. Inoculum

Inoculum was collected (8/11/2013) from a mesophilic anaerobic digester processing food waste at Scottish Water's Deerdykes site (Cumbernauld, UK; 55.9° N, −4.0° W) and stored in steralised plastic containers while transferred to the lab (during *ca.* 30 min). On arrival the inoculum was passed through a 1.6 mm mesh sieve [26] under a nitrogen atmosphere into a large (2000 cm^3) pre-cleaned storage vessel; the headspace was then flushed with nitrogen for 2 min to maintain anaerobic conditions and the vessel sealed. Sieving was found to reduce interference from larger undigested particles in blank assays. Inoculum was then stored in an incubator at 36 ± 2 °C to de-methanise for 5 days [27]. The storage vessel was purged daily using a small release clip on the end of a tube attached to a port on the vessel. This was to release the pressure in the vessel before resealing immediately. After storage the inoculum was then added to the anaerobic reactors. The inoculum was characterised for the specific methanogenic activity, total solids (TS), volatile solids (VS) and pH.

2.3. Experimental set-up

Batch experiments in glass serum bottles (Wheaton, Sigma Aldrich) with a working volume of 162.5 cm^3 each (125 cm^3 liquid volume) were used to provide closely monitored and controlled conditions. For each reactor 50 cm^3 of inoculum was added, followed by 12.5 g of each substrate (or mixture of substrates) which were diluted to approx. 10% solids in the reactor to achieve an initial inoculum to substrate (I:S) VS ratio of 1 [28]. Reactors were then flushed for 2 min with a stream of N_2 to ensure anaerobic conditions in their headspace and sealed with a perforated butyl rubber stopper and aluminium crimp cap. Following, 6 mm Nylon tubing was pushed through the hole in the cap and sealed with a 2-way push fit valve (Pneu-Hydro Products, UK) to maintain anaerobic conditions, a second nylon tube was fitted to the outlet of the valve and capped with a push fit stopper. Reactors were initially mixed by vortexing for 20 s prior to incubation to ensure thorough mixing. Valves remained off unless sampling was taking place and a cap seal was fitted to the top of the second tube to prevent any gas escaping. Caps were removed to allow for headspace sampling. The headspace of each reactor was calculated by subtracting the added amount of substrate and inoculum from the total volume of the