Resources, Conservation & Recycling 139 (2018) 114–121

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Life cycle assessment of portable two-stage anaerobic digestion of mixed food waste and cardboard

Claudia Isola[a], Heidi L. Sieverding[a], Caitlin M. Asato[b], Jorge Gonzalez-Estrella[b], David Litzen[c], Patrick C. Gilcrease[b], James J. Stone[a,*]

[a] Department of Civil and Environmental Engineering, South Dakota School of Mines & Technology, Rapid City, SD, 57701, USA
[b] Department of Chemical and Biological Engineering, South Dakota School of Mines & Technology, Rapid City, SD, 57701, USA
[c] Litzen Process Consulting Inc., Rapid City, SD, 57701, USA

ARTICLE INFO

Keywords:
Biogas production
Anaerobic digestion
Life cycle assessment
Organic waste treatment
Waste reduction

ABSTRACT

Biogas produced from organic waste can reduce waste and produce renewable energy and is a viable waste treatment alternative for remote encampments. Portable, small-scale anaerobic digestion (AD) units can be used to sustainably produce biogas in remote areas and reduce landfilled waste. This project investigated the life cycle impacts of a portable AD unit and the effects of organic loading rate (8–32 g chemical oxygen demand (COD) L^{-1} d^{-1}) and waste composition (food versus cardboard waste ratios of 35:65 and 65:35) on biogas production efficiency. Optimal biogas production was obtained using a 65% food to 35% cardboard waste mixture and a mid-range organic loading rate (16 g COD L^{-1} d^{-1}); this scenario also yielded the lowest climate change impact [37.4 ± 0.7 g CO_2 eq per kg COD waste] due to greater biogas conversion efficiency. However, the overall life cycle impacts of biogas production were not significantly affected by waste mixtures or feed rates in the AD portable system and experiments evaluated. Life cycle impacts due to portable AD processing were overall agnostic to feedstock variability. Thus, waste type and volume variations generated by encampments with fluctuating populations can likely be accommodated by the portable AD system without substantially affecting short term process sustainability. Portable AD system biogas generation rates were comparable to conventional, full-scale waste to energy facilities, while combustion impacts were more sustainable than those associated with conventional fossil fuels. Portable AD units represent a sustainable energy resource, waste reduction, and landfill alternative for remote areas.

1. Introduction

Solid waste is a critical global issue and is epitomized by United States' (US) waste production. In 2014, the US generated 258 million tonnes of municipal solid waste (MSW), averaging two kg (4.4 lbs.) per person per day (USEPA, 2016). Most this MSW was organic waste in the form of food waste (FW) and paper and paperboard (PPB), 15% and 27% respectively. Organic wastes composed 36% of US landfilled MSW (136 million tonnes per year) after removal of recyclables (USEPA, 2016). Landfilling has potential consequences such as greenhouse gas emissions, gas and leachate generation, as well as possible health hazards, fires and explosions, damage to vegetation, landfill settlement, and groundwater and air pollution (El-Fadel et al., 1997; Emberton and Parker, 1987). Therefore, biodegradable organic waste represents not only a potential environmental hazard, but also wasted energy potential. Producing energy from waste is an alternative management option which may reduce the environmental impact of waste disposal. Anaerobic digestion (AD) is an organic waste treatment option from which renewable biogas (i.e. methane) can be collected in the absence of oxygen to use in energy and/or heat generation (Tagliaferri et al., 2016). According to El-Fadel et al. (1997), AD has advantages over landfilling with gas collection because it is more efficient (volatiles elimination efficiency of ~70% for AD versus ~7% for landfilling with gas collection), occupies a smaller footprint, and presents smaller pollution risks. Therefore, a portable AD system may be an alternative option for waste treatment in small and isolated encampments such as military forward operating bases, temporary refugee camps, and disaster areas. Installation of advanced solid waste treatments in isolated areas is hampered by community investment, ability, and willingness as well as camp site duration (Medina and Waisner, 2011). Portable AD treatment technologies are an opportunity to reduce solid waste volume and generate energy in minimal or damaged infrastructure areas,

* Corresponding author.
E-mail address: James.Stone@sdsmt.edu (J.J. Stone).

https://doi.org/10.1016/j.resconrec.2018.08.008
Received 7 July 2017; Received in revised form 9 February 2018; Accepted 13 August 2018

reducing also the need to transport fuel across conflict or disaster zones (Asato et al., 2016).

Many factors affect AD process design and operational efficiencies, such as feedstock characteristics, reactor construction, and operation conditions (Hawkes, 1980; Zhang et al., 2007). To equate differing feedstock qualities for methane conversion under anaerobic conditions, the chemical oxygen demand (COD) is used because it can be used to compare production potential. Food waste contains high amounts of water-soluble organics that can rapidly convert to volatile fatty acids (VFAs) at early stages of digestion (Cho et al., 1995) and cause a pH drop detrimental to methane generation. Meanwhile, PPB products such as cardboard (CB) are lignocellulosic feedstocks that do not readily biodegrade under anaerobic conditions (Verma, 2002). As a result, FW mixed with CB has been identified as a promising substrate for methane (CH_4) production; however, differences in degradability were not conducive to synergistic co-digestion in a single reactor (Asato et al., 2016). The faster digestion of mixtures with a high FW composition inhibited methanogenesis due to VFA accumulation (Asato et al., 2016).

This tendency towards VFA accumulation makes multi-stage AD more appropriate to maximize CH_4 production. Multi-stage AD is a well-established technology wherein VFA production occurs primarily in a separate reactor from CH_4 production, allowing VFAs to accumulate in the first stage without inhibiting the methanogenic microbes (Pohland and Ghosh, 1971). This allows for higher loading rates of easily-degraded feedstocks such as FW. Numerous benefits and challenges are associated with designing AD systems and stages. Factors such as temperature, pH, C/N ratios, feedstock variability, organic loading rates (OLR), retention time, accelerant use, cost, reactor design, regulations, and treatment targets and goals affect AD design selection and treatment efficiency (Hagos et al., 2017; Mao et al., 2015; Xiao et al., 2018). This portable AD unit prototype was designed with the goals of optimizing CH_4 production, simplifying operation, and improving process stability.

Methodologies such as LCA are used to assess environmental impacts of a product or process from raw material to end of life ("cradle-to-grave"), evaluating all stages of materials processing, manufacturing, distribution, use, and disposal (Finkbeiner et al., 2006; Guinee, 2002). LCA has been used to evaluate various waste treatment scenarios and past studies have shown that AD provides a sustainable waste-to-energy option; however, no study to date has evaluated a portable AD. Research has demonstrated that AD waste energy recovery processes from food waste can be an economical (Ahamed et al., 2016) and/or sustainable (Bernstad Saraiva Schott et al., 2016) waste avoidance alternative when compared to landfilling, incinerating, or composting (Arafat et al., 2015; Evangelisti et al., 2014; Opatokun et al., 2017; Xu et al., 2015). However, waste composition, such as high levels ($> 5\%$) of oil or lipids in FW, has been shown to reduce the benefits of AD (Ahamed et al., 2016). Xu et al. (2015) performed an LCA of FW treatment options in China that identified diesel use during transportation as a factor which increased FW disposal impacts, supporting the hypothesis that on-site AD waste processing systems could reduce transportation-related impacts. A review of food waste disposal LCAs showed that energy substitution and system boundary assumptions significantly affected findings, systems which included fossil fuel, energy crop, or manure substitutions showed greater AD greenhouse gas (GHG) avoidances (-2084 to 28 kg CO_2 eq per tonne wet FW) than those without (45–71 kg CO_2 eq per tonne wet FW) (Bernstad Saraiva Schott et al., 2016). In addition, life cycle impacts are significantly affected by AD design (Xiao et al., 2018), waste feedstock blends or co-digestion (Edwards et al., 2017), OLR (Di Maria et al., 2016), and waste feedstock and biogas quality (Chiu and Lo, 2018). Waste is spatially and temporally variable in both quantity and quality, complicating evaluation of waste management pathways (Pierie et al., 2016). The inconsistency of these factors makes AD comparison between locations and systems difficult, necessitating full life cycle understanding and caution when evaluating potential benefits.

The purpose of this study was to determine and evaluate the life cycle impacts of FW and CB co-digestion using a portable, multi-stage AD to process organic solid waste and generate biogas for local heating with respect to major environmental impacts, cumulative energy demand (CED), and waste prevention. The goal was to understand the sensitivity of the portable AD to feedstock and OLR changes, effect of scale, and heat source as well as identifying operating conditions which provided the best biogas yield and lowest impact. The environmental impact of portable AD generated biogas used as a heat source was compared to traditional heat sources such as natural gas, coal, and diesel to assess renewable fuel use. The efficiency of the portable AD was further evaluated by comparing its energy efficiency to traditional, full-scale waste disposal systems with energy recovery operations to assess scale impacts.

2. Methods

An LCA evaluation was conducted using an attributional approach to estimate environmental life cycle impacts of using AD treatment of FW and CB with feedstock quality expressed as COD and varying processing (loading) rates to produce enough biogas to generate 1 MJ of heat. Waste was assumed to be manually sorted prior to processing. Waste input into the portable AD and was assumed to be monitored for foreign objects and non-organic waste. Heat was assumed to be locally used to maintain AD operational temperature or for water heating and/or steam generation. The LCA model was developed following the standards from International Organization for Standardization (ISO) 14040 and 14044 (ISO, 2006a, b), using SimaPro 8.2.0 modeling software (Pré Consultants, Netherlands) and EcoInvent 3.2 (EcoInvent, Switzerland) life cycle inventory database (Wernet et al., 2016) for specific process inventories.

The ASPEN Plus (v8.8; AspenTech, Bedford, Massachusetts) chemical process optimization software was used to develop a portable AD model and prototype based on laboratory test results (Asato et al., 2017) and to parametrize LCA model inputs and biogas yields. The environmental impacts of AD waste treatment scenarios using varied FW and CB compositions and loading rates were evaluated. The results of these analyses were compared to business-as-usual scenarios available within EcoInvent with two goals in mind, understanding the effects of scale on waste disposal alternatives and the impacts of switching from fossil fuels currently in use to biogas. The biogas generated by the treatment was theoretically used as heat source and compared to conventional small-scale heat sources such as coal, natural gas, and diesel. An energy demand versus recovery analysis was conducted to compare efficiency of a small-scale portable AD prototype with conventional large-scale landfill, incineration, and biogasification waste treatment processes available within EcoInvent.

2.1. *Portable anaerobic digester*

To parametrize the models, characterize varying waste composition and AD settings, and assist in scaling the AD prototype, laboratory tests conducted used a two-stage reactor developed to emulate planned prototype AD processes (Asato et al., 2017). In brief, the first stage was a continuously-stirred tank reactor (CSTR) with a three-liter benchtop fermentor (Applikon Biotechnology B.V.; Delft, Netherlands) and a working volume of one liter. The fermentor included a mechanical impeller, which was set to agitate continuously at 150 rpm. The head plate was fitted with a plastic inlet-outlet tube with an inner diameter of approximately 0.95 cm to accommodate flow of large suspended solids. The CSTR was seeded with five grams of volatile suspended solids (VSS) per liter of sludge. Feeding and effluent removal were performed daily with a peristaltic pump through the inlet-outlet tube. Influent and effluent flow rates were both 0.5 L d^{-1} to maintain a steady working volume. The influent mixture contained FW and CB diluted in synthetic human wastewater (WW) to achieve the desired concentration. Biogas