Waste Management xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Waste Management

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

Experimental and feasibility assessment of biogas production by anaerobic digestion of fruit and vegetable waste from Joburg Market

S.O. Masebinu [a,*], E.T. Akinlabi [a], E. Muzenda [b], A.O. Aboyade [c,d], C. Mbohwa [c]

[a] Department of Mechanical Engineering Science, University of Johannesburg, South Africa
[b] Department of Chemical Engineering Technology, University of Johannesburg, South Africa
[c] Department of Quality and Operations Management, University of Johannesburg, South Africa
[d] United States Agency for International Development/Southern Africa, Pretoria, South Africa

ARTICLE INFO

Article history:
Received 11 October 2017
Revised 31 January 2018
Accepted 6 February 2018
Available online xxxx

Keywords:
Anaerobic digestion
Techno-economics
Fruit waste
Mono- digestion
Waste management
Biogas

ABSTRACT

Substrate-induced instability of anaerobic digestion from fruit and vegetable waste (FVW) results in low biogas yield. In this study, substrate management through fruit to vegetable mix ratio in a two-stage semi-continuous digester was investigated as a pathway for optimality of yield. The experiment conducted over 105 days with 62.52 kg of FVWs sourced from Joburg Market, South Africa showed that a stable process was achieved at a fruit to vegetable waste mix ratio of 2.2:2.8. At this ratio, optimal organic loading rate ranged between 2.68 and 2.97 kg VS/m^3-d which resulted in a specific biogas yield of 0.87 Nm^3/kg VS with 57.58% methane on average. The results of the experimental study were used as a feasibility assessment for a full-scale 45 tonnes/d plant for Joburg Market considering three energy pathways. The plant will produce 1,605,455 Nm^3/y of biogas with the potential for offsetting 15.2% of the Joburg Market energy demand. Conversion of all biogas to biomethane was the most economically attractive energy pathway with a net present value of $2,428,021, an internal rate of return of 16.90% and a simple payback period of 6.17 years. This route avoided the greenhouse gas emission of 12,393 tonnes CO_2, eq. The study shows that the anaerobic digestion of FVWs as sole substrate is possible with financial and environmental attractiveness.

1. Introduction

An amalgamation of several factors related to rapid urbanisation within the City of Johannesburg (CoJ) in South Africa has made the efficient management of its municipal solid waste (MSW) challenging. The challenge is expected to be exacerbated since MSW generation is projected to rise from 1.6 to 3.6 million tonnes/year should its population reach 9.2 million by 2040 (Aurecon South Africa (Pty) Ltd, 2015). A study in 2016 revealed that the organic percentage of MSW collected from households, restaurants and Joburg Market -a fruit and vegetable market wholly owned and operated by Johannesburg Metropolitan Municipality- was 34%, 14% and 93% by weight respectively (Masebinu et al., 2017b). The current management system for MSW disposal is landfilling. However, CoJ's landfills are currently estimated to have between 5 and 11 years lifespan. As the MSW generation rate increases (e.g. from between 0.35 and 1.6 kg/capita/day in 2003 to between 0.92 and 1.91 kg/capita/day in 2015 (Aurecon South Africa (Pty) Ltd, 2015; Ogola et al., 2011)), it can be reasonably expected that the projected lifespan may be impacted. The establishment of new landfills within and around CoJ's metropolitan area is an unlikely option because of a lack of suitable and available land (City of Johannesburg, 2011), which suggest the urgent need to consider other options for its MSW disposal.

As part of an integrated MSW management plan, the CoJ is interested in anaerobic digestion (AD) technology for the treatment of highly biodegradable wet organic MSW, for example, fruit and vegetable waste (FVW) from Joburg Market (JM). JM receives farm produce from about 5000 farmers across South Africa generating an average of 47 tonnes/d of FVWs which are sent to the landfill. The disposal of FVWs in landfills come with specific challenges, most of which are related to high moisture content and a high degree of perishability (Scano et al., 2014). The fast degradation rate of FVW leads to the generation of greenhouse gases (GHG), specifically methane (CH_4) and carbon dioxide (CO_2) (Asquer et al., 2013). Aside from the climate change impact, disposal cost and sale losses due to the quantity of FVWs generated directly impacts the operating cost of the wholesale market. On the other hand, the physicochemical characteristics of FVW make

* Corresponding author.
E-mail address: masebinity@gmail.com (S.O. Masebinu).

https://doi.org/10.1016/j.wasman.2018.02.011
0956-053X/© 2018 Published by Elsevier Ltd.

Nomenclature

Acronyms	Meaning
V, V_v	volume of biogas [Nl/d],[Nm^3/h]
T_{BG}	ambient temperature [°C]
P_{BG}	ambient pressure [N/m^2]
N_c	number of tips per day [count/d]
V_c	volume of biogas per tip [l/count]
V_{pH_5}	titration volume to pH 5 [ml]
$V_{pH_{4.4}}$	titration volume to pH 4.4 [ml]
V_{dig}	volume of digestate [ml]
$N_{H_2SO_4}$	acid normality [M]
M_{CaCO_3}	molar mass of $CaCO_3$
Q_{dig}	total thermal energy losses [kW]
r	radius of digester [m]
$T_{o,min}$	minimum outside temperature [°C]
$h_{air,forced}$	forced air convention [W/m^2 °C]
$t_{insulation}$	thickness of insulation [mm]
K_{ps}	heat conduction coefficient of insulation [W/m^2∘C]
$h_{water,free}$	free water convection [W/m^2∘C]
t_{pvc}	thickness of digester dome cover [mm]
K_{pvc}	heat conduction coefficient of dome cover [W/m^2∘C]
$h_{air,free}$	free air convection [W/m^2∘C]
K_{soil}	heat conduction of soil [W/m^2∘C]
Q_{sub}	thermal energy to raise substrate to digester temperature [kW]
m_{sub}	mass of substrate [kg/d]
$C_{specific}$	specific heat capacity of substrate [kJ/kg°C]]
T_{dig}	digester operating temp [°C]
T_{sub}	substrate delivery temperature [°C]
CF_t	annual after-tax cash flow [$]
i	discount rate [%]
t	time [years]
CC_{CHP}	capital cost of the CHP [$]
CC_{BM}	capital cost of biogas scrubber [$]
P_p	installed power of CHP [kW]
n	project life [years]

it particularly suitable as feedstock for AD (Bouallagui et al., 2003; Wu et al., 2016). The choice of AD inherently introduces a multi-objective approach to energy generation, creation of secondary raw material and reduction of environmental burden.

AD is a biological method that can be used to reduce and stabilise organic matter of various types in an oxygen-starved environment by a consortium of bacteria and archaea while simultaneously producing an energy carrier called biogas (Schnürer et al., 2017; Wang et al., 2017). Biogas is mainly composed of CO_2 and CH_4 and finds application in heat, electricity generation and as a vehicular fuel (Parajuli et al., 2014; Shen et al., 2015). Biogas generated from FVWs of JM can offset part of the 22,431 MW h/year of electricity consumed at the cost of $2.5 million/year (Market, 2016). Aside biogas, a sludge-like by-product called digestate, that is potentially useful for agronomic applications, is also produced (Mangwandi et al., 2013). It can, therefore, be summarised that AD technology proffers energy, environmental, waste management and socio-economic benefits (Amoo and Fagbenle, 2013; Fallde and Eklund, 2015; Mangwandi et al., 2013; Olsson and Fallde, 2015; Tan et al., 2015). Although AD offers many benefits, the process presents some limitations mainly due to the duration for stabilisation of organic waste, slow degradation of volatile solids, fluctuating biogas yield rate and substrate-induced process instability (Khalid et al., 2011; Pavi et al., 2017). AD process stability and biogas yield rate are strongly related to the source and composition of the substrate, process and operational conditions and partly, the type of digestion technology used (Muhammad Nasir et al., 2012; Raposo et al., 2011; Ratanatamskul et al., 2015). The extent of stability of an AD process can be adversely affected by the excessive accumulation of volatile fatty acid (VFA) and ammonia. The accumulation of VFA results in acidification of the AD process thereby inhibiting the methanogenic activity (Asquer et al., 2013; Scano et al., 2014; Wu et al., 2016). AD of FVW as the sole substrate is challenging due to the tendency to accumulate VFA caused by the degradation of highly soluble simple sugar (Lebuhn et al., 2014; Wang et al., 2014).

Several studies have reported AD instability resulting from digesting FVWs as sole substrate (Alkanok et al., 2014; Bouallagui et al., 2003; Bouallagui et al., 2005; Sitorus et al., 2013). Maile et al. (2016) terminated the digestion of JM's FVW after four days due to acidification problem encountered during the batch experiment. A conventional approach for managing the instability caused by rapid acidification is the application of alkaline chemicals to adjust the AD pH to levels between 6.8 and 7.2, thereby neutralising the acidification process (Gao et al., 2015). Another approach is to make use of two-stage digestion that promotes different types of oxidation and reduction reactions, pH optima and growth rate of acidogens and methanogens to increase process efficiency (Ganesh et al., 2014; Ward et al., 2008; Wu et al., 2016). The two-stage approach has the advantage of hydrolysing the substrate and buffering organic loading rate (OLR) in the first stage. In the second stage, the hydrolysed and homogenised substrate can be easily digested by the methanogens. Co-digestion of different substrates provides buffering capacity to the digester (Fonoll et al., 2015; Ganesh et al., 2013; Wang et al., 2014). It also increases the biodiversity of the microbial community that facilitates the AD process (Wang et al., 2018). The microbial population in the digester and the biogas yield is partly dependent on the ratio of the different types of waste within the substrate mix (Lin et al., 2012). Pavi et al. (2017) reported higher biogas yield and process stability during co-digestion of food waste with FVWs at a ratio of 1:3 compared to mono-digestion. Huang et al. (2016) found optimal mix ratio at 3:1 of Aloe vera waste to dairy manure. Li et al. (2015) found a ratio of rice husk to pig manure of 1:1 as optimum. Molinuevo-Salces et al. (2012) reported a 1:1 mix ratio as optimal for AD of vegetable waste with pig manure. Furthermore, Wang et al. (2018) observed that increasing fraction of FVWs by 5% during co-digestion increased CH_4 yield by 22.4%. Cabbai et al. (2013) and Koch et al. (2016) showed that co-digestion could increase CH_4 yield rate by 18–48%. Aside co-digestion, management of total solids (TS) concentration in the substrate has been reported to improve the performance of digesters treating FVWs. Bouallagui et al. (2003) found that a substrate with TS concentration <6% wet weight favours process stability but at the expense of high biogas yield. Also, Alkanok et al. (2014) digested FVWs with a 5% TS concentration and reported high volatile solid (VS) degradation.

Thermal and chemical pre-treatment is another viable way to reduce tendencies of instability when digesting FVWs as reported by Dahunsi et al. (2016). Other stabilisation approach includes hydraulic retention time management (Bouallagui et al., 2003; Di Maria et al., 2015), organic loading rate (Aboudi et al., 2015; Di Maria et al., 2015), digestate recycling (Zuo et al., 2015), elemental composition adjustment (Wang et al., 2012; Wang et al., 2013),

Please cite this article in press as: Masebinu, S.O., et al. Experimental and feasibility assessment of biogas production by anaerobic digestion of fruit and vegetable waste from Joburg Market. Waste Management (2018), https://doi.org/10.1016/j.wasman.2018.02.011