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# Can anaerobic digestion of sugar beet pulp support the circular economy? a study of biogas and nutrient potential

S Suhartini<sup>1</sup>, S Heaven<sup>2</sup> and C J Banks<sup>2</sup>

<sup>1</sup>Department of Agro-industrial Technology, Faculty of Agricultural Technology, Universitas Brawijaya, Malang, Indonesia

<sup>2</sup> Faculty of Engineering and the Environment, University of Southampton, Southampton, United Kingdom

E-mail: ssuhartini@ub.ac.id

**Abstract.** Anaerobic digestion (AD), known as a biological process without oxygen to convert complex organic materials into biogas, is capable of processing large tonnage quantities of biomass, such as sugar beet pulp (SBP). In addition to biogas production, its use allows nutrients and organic carbon recycle back to agriculture through the spreading of digestate. Digestate still contains high amount of nutrients (N, P, K) for use as biofertiliser. The aims of this research were to determine biogas/methane potential as a baseline for comparison with performance in semi-continuous digestion, and to determine nutrient and potentially toxic elements (PTE) of digestate fractions with respect to their potential for utilisation in agriculture. The Biochemical Methane Potential (BMP) test was performed in triplicate against blank and positive controls over a period of 28 days with gas measured at regular intervals. Semi-continuous AD of SBP was operated under mesophilic and thermophilic condition for 206 and 165 days. The results indicated that SBP is a very promising feedstock for AD, with the average BMP of 0.321 l CH<sub>4</sub> g<sup>-1</sup> VS and biogas potential of 0.605 l g<sup>-1</sup> VS. Under semi-continuous operation, SBP also demonstrated positive results. Digestates from mesophilic and thermophilic AD of SBP contained useful quantities of N, P and K, with an acceptable Ni concentration in accordance to limits for PTE. These results suggest that digestate has the potential to be utilised on agricultural and arable land. This study illustrated the positive effects of applying AD to the achievement of economic savings and environmental-friendly performance.

## 1. Introduction

Sugar Beet Pulp (SBP) is the solid organic residue that arises from sugar beet processing and is generated worldwide, in particular in Europe and the USA. In the UK, which has an annual SBP production of around of 500,000 tones year<sup>-1</sup> [1], it is mainly used as cattle feed as it contains all the basic constituents of forage including fibre and amino acids.

Anaerobic digestion (AD) plays an important role in providing a source of renewable energy. In addition to biogas production, AD as one of the promising technology for treating biomass produces digestate, which still rich in organic matter and macro nutrients (such as N, P dan K), thus suitable for biofertiliser or soil conditioner [2]. Also, AD is capable of processing large tonnage quantities, as well



as the nutrient and organic carbon can be recycled back to agriculture through the spreading of digestate. The process also gives a reduction in biological risks and the potential for malodour [3]. AD also offers economic benefits through reduced material handling and transport costs and better revenue returns from energy production compared to the animal feed market [4-5].

The use of digestate as alternative soil conditioner or biofertiliser is likely to make a beneficial contribution in reducing negative impact on the environment as opposed to the use of synthetic fertilisers. It is because digestate usage can reduce nitrogen losses to groundwater, surface water and the atmosphere and/or minimise the carbon footprint through a reduction in green house gasses (GHG) emissions [6]. Although digestate may contain useful nutrients, it can also contain potentially toxic elements (PTE) (e.g. Cd, Ni, etc.) or pathogens [7]. Therefore, application of digestate to agricultural land is normally regulated to fulfil the requirements of both agricultural best practice and environmental protection

Before implementing AD at continuous or semi-continuous condition, studies under batch condition is necessary. This is known as the Biochemical Methane Potential (BMP) test which is used to determine the biodegradability of a substrate under anaerobic conditions by monitoring the cumulative methane production during the test period [8]. This measurement can provide important information including the anaerobic digestibility and potential biogas (methane) production from substrates which is useful for evaluating, designing, and optimising the AD process [9]. Besides measuring the conversion of organic matter to methane, the BMP test can also be used to determine the residual organic material amenable to further anaerobic treatment, the non-biodegradable fraction remaining after treatment, and the potential efficiency of AD for a particular substrate [10].

Therefore, this study was aimed at determining biogas/methane potential from SBP as a baseline for comparison with performance in semi-continuous digestion, as well as determining nutrient and PTE of digestate fractions with respect to their potential for utilisation in agriculture.

## **2. Materials and Methods**

### *2.1. Feedstocks and inoculums*

SBP was collected fresh from British Sugar's Wissington Factory, Kings Lynn, UK. The inoculum for BMP test was collected from a mesophilic digester treating municipal wastewater biosolids (Millbrook Wastewater Treatment Works, Southampton, UK). The inoculum for semi-continuous trials under mesophilic condition was prepared by mixing 1 part of digestate taken from an anaerobic digester treating sugar beet pulp (British Sugar, Wissington, UK) with 1 part of digestate taken from Millbrook Wastewater Treatment Works. While, the thermophilic digesters used an inoculum taken from this mesophilic municipal wastewater biosolids digester, which was then acclimated to thermophilic conditions.

### *2.2. BMP test set-up*

The BMP test in this work was performed in 550 ml sealed bottles placed in a temperature controlled water bath at 37 °C. The inoculum-to-substrate (I/S) ratio used was 4:1 on a VS basis and the test was run over a period of 28 days. No supplements were added, as the inoculum used was known to be sufficiently rich in the required nutrients. Biogas was collected in perspex cylinders by displacement of a 75% saturated sodium chloride solution acidified to pH 2, in order to reduce losses of methane by dissolution. The height of the solution in the collection cylinder was recorded manually for a certain interval on a daily basis. Vapour pressure and salt solution density were taken into account in correction of gas volumes to a standard temperature and pressure (STP) of 0 °C and 101.325 kPa [11]. Samples for gas composition analysis were taken from the cylinders each time they were refilled, at intervals of no more than 7 days to avoid the risk of overfilling or losses of methane. The bottles were shaken each day before the gas level measurement was taken to provide mixing. Samples were run alongside blanks (inoculums only) and positive controls (cellulose powder from Sigma-Aldrich, Dorset-UK), all in triplicate.

### 2.3. Semi-continuous trials set-up

The experiments were carried out in four mesophilic (37 °C) and four thermophilic (55 °C) digesters with a 4-litre working volume. These were all seeded with an inoculum as described in section 2.1. Duplicate digesters were run at each temperature at organic loading rate (OLR) of 4 and 5 g VS l<sup>-1</sup> day<sup>-1</sup> for 3 hydraulic retention time (HRT), equivalent to 206 and 165 days. Each digester received trace element (TE) supplementation based on the amount of feedstock added.

### 2.4. Analysis

TS and VS determination was based on Standard Method 2540 G [12]. pH was measured using a Jenway 3010 meter (Bibby Scientific Ltd, UK) with a combination glass electrode, calibrated in buffers at pH 7 and 9.2. Total ammonia nitrogen (TAN) analysis was based on Standard Method 4500-NH<sub>3</sub> B and C [12]. Alkalinity measurement was based on Standard Method 2320B [12]. Biogas composition was quantified using a Varian Star 3400 CX gas chromatograph (GC), (Varian Ltd, Oxford, UK). Biogas volume was measured using a weight-type water displacement gasometer [11]. Nitrogen (N) was measured using Total Kjeldhal Nitrogen (TKN) analysis. Phosphorus (P) content of the digested sample was determined using a UV-Visible scanning spectrophotometer (Cecil 3000 series, Cecil Instruments). Potassium (K) was measured using a Spectr AA-200 Atomic Absorption Spectrometer (Varian, Australia). Trace element was analysed using ICP-MS at Severn Trent Laboratory Limited, UK. This was measured according to Standard Method 2510 [12] using a LF330 conductivity meter (WTW, Germany). COD was measured by the closed tube reflux method [12]. Turbidity was measured according to Bruus et al. [13] at a wavelength of 650 nm.

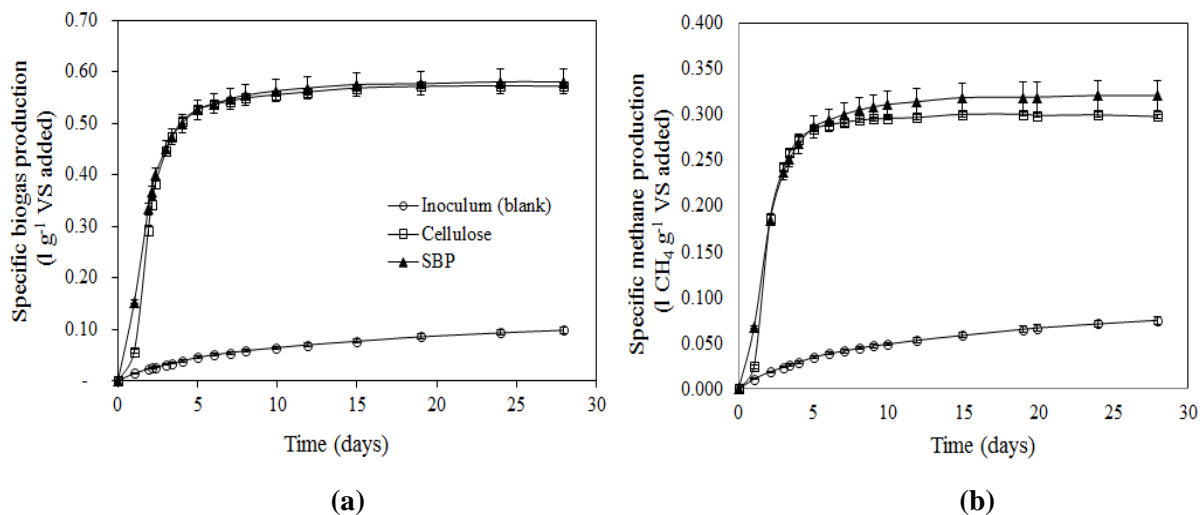
## 3. Results and Discussion

The characterisation on SBP in this study has been reported in Suhartini et al [14]. The results indicated a high potential for conversion to biogas due to its high VS content at value of 225.5 g kg<sup>-1</sup> WW (or 93.14 % of TS) and high calorific value of 16.86 MJ kg<sup>-1</sup> TS.

### 3.1. BMP test results

Figure 1 shows that the specific biogas and methane production of the SBP and the cellulose positive controls against the blank samples. The blank samples reached a stable value after approximately 14 days with 28-day specific biogas productions of 0.110, 0.092, and 0.092 l g<sup>-1</sup> VS, giving an average value of 0.098 l g<sup>-1</sup> VS. The positive controls had a rapid biogas production after a short lag time and reached a plateau after 10 days: the specific biogas yields were 0.566, 0.568 and 0.581 l g<sup>-1</sup> VS with an average value of 0.572 l g<sup>-1</sup> VS (Figure 1a). SBP with fresh inoculum demonstrated the same trend as the positive control, showing a short lag time and reaching a plateau after 10 days with net specific biogas productions of 0.577, 0.584, and 0.653 l g<sup>-1</sup> VS, respectively, thus giving an average value of 0.605 l g<sup>-1</sup> VS. This value was slightly lower than the values of 0.664 l g<sup>-1</sup> VS reported in a previous study [15] for a different batch of material from the same source.

Figure 1b shows the specific methane production of the SBP and the positive controls against the blank sample. The blank samples had specific methane productions of 0.084, 0.071, and 0.071 l CH<sub>4</sub> g<sup>-1</sup> VS, respectively; with the average value 0.075 l CH<sub>4</sub> g<sup>-1</sup> VS. The positive controls had a specific methane yield of 0.296, 0.295 and 0.303 l CH<sub>4</sub> g<sup>-1</sup> VS with an average of 0.298 l CH<sub>4</sub> g<sup>-1</sup> VS. The positive controls showed reasonable agreement and the average specific methane yields were typical of values obtained for these materials, indicating the suitability of the assay conditions. Using fresh inoculum gave values of 0.302, 0.307 and 0.355 l CH<sub>4</sub> g<sup>-1</sup> VS with an average BMP of 0.321 l CH<sub>4</sub> g<sup>-1</sup> VS. This BMP value is fairly typical for crop and agro-waste substrates which have high cellulose content and relatively low lignin [16].



**Figure 1.** Specific biogas (a) and methane (b) production from the BMP test: the blank samples, positive control, and SBP. Data are expressed as means of triplicate samples and bars represent range

### 3.2. Semi-continuous digestion performance

Although SBP was shown to be easily degraded under ideal conditions in the BMP test, with a good gas yield and VS destruction, in practice semi-continuous digestion under mesophilic conditions proved to be much more difficult, particularly at high OLR. Details findings on semi-continuous digestion performance has been reported in our previous study [14]. This study reported that thermophilic digestion was superior and better suited to the digestion of SBP when compared to mesophilic digestion. It could operate at higher organic loading rates, produced a higher specific methane yield, and offered better solids destruction. The mesophilic process when operated at a high organic loading rate suffered further disadvantages in that it showed a relatively high residual methane production, indicating a potential for methane emissions during any digestate storage phase. The major finding, however, was that thermophilic digestion was unlikely to result in foaming problems in the digester. The results for SBP therefore support those from other studies that have reported a better performance from thermophilic digestion than mesophilic in terms of: organic matter destruction, process stability, and specific biogas and methane production.

In this regards, it seems that in the case of SBP, operating AD at thermophilic condition is more preferable and stable.

### 3.3. Digestate characteristics

The characteristics of the whole digestate, solid and liquid fractions are presented in Table 1. Digestates from mesophilic and thermophilic AD of SBP contained useful quantities of N, P and K, with an acceptable Ni concentration with respect to limits for PTE. After separation, both liquid and solid fractions of digestates still have a high amount of nutrient N. These results confirm that the digestate has potential for application on agricultural land to substitute the use of mineral N, P and K fertiliser both as whole digestate, solid and/or liquid fraction.

In addition, the concentrations of TKN and ammonia N in the supernatant were in the range of 1 - 2 g l<sup>-1</sup> (assumed density of supernatant = 1 kg l<sup>-1</sup>), very high for directly discharge to watercourses. Furthermore, the removal of ammonia N in wastewater treatment is energy intensive as it requires ~4.3 g O<sub>2</sub> per g N while typical transfer efficiencies in aeration plants range from 0.9 to 3.1 kg O<sub>2</sub> kWh<sup>-1</sup> [17]. There is considerable interest in development of technologies to recover N from liquid supernatants though struvite precipitation etc. [18], but these are not considered further here.

Furthermore, this study has also determined the system boundary for carbon, energy and nutrient footprint from AD of SBP (Figure 2), in both mesophilic and thermophilic conditions. The system

boundary includes the anaerobic digestion process, feedstock and digestate transportation, digestate dewatering and application, and biogas utilisation/upgrade. The calculation showed that the potential mineral N fertilizer replacement was in the range of 14-18% of the net savings in GHG emissions, from 8 different scenarios (Figure 3). This indicates that the use of digestate as a biofertiliser has a useful role to play in terms of carbon balance or GHG emissions or environmental contribution as it makes up about 1/3 of the emissions saving in these cases.

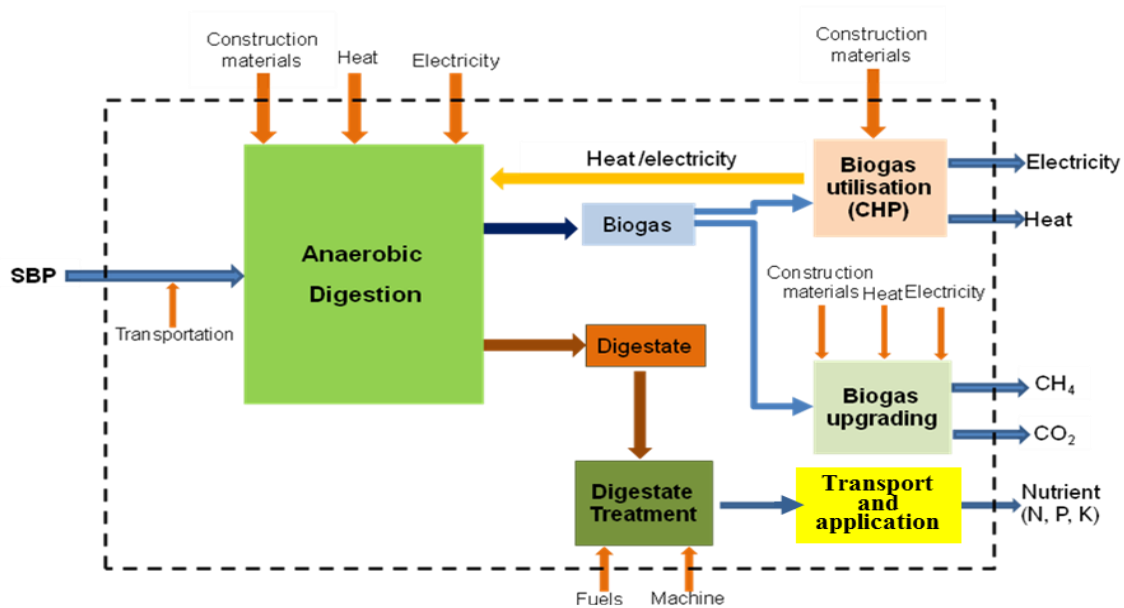
**Table 1.** Nutrient and trace elemental content of mesophilic and thermophilic digestates.

Parameter	Mesophilic						Thermophilic					
	OLR 4			OLR 5			OLR 4			OLR 5		
	WD	SL	SF	WD	SL	SF	WD	SL	SF	WD	SL	SF
<i>Macro nutrient (g kg<sup>-1</sup> WW)</i>												
TKN (N)	4.04	1.54	8.15	3.86	1.75	8.09	4.22	1.81	8.19	4.34	1.60	8.47
P	0.61	-	-	0.47	-	-	0.80	-	-	0.77	-	-
K	0.72	-	-	0.80	-	-	0.80	-	-	0.94	-	-
<i>Elemental analysis (mg kg<sup>-1</sup> WW)</i>												
Co	0.27	-	-	0.23	-	-	0.34	-	-	0.30	-	-
Fe	66.16	-	-	39.73	-	-	15.32	-	-	12.96	-	-
Mo	0.14	-	-	0.19	-	-	0.12	-	-	0.11	-	-
Ni	0.74	-	-	0.94	-	-	0.68	-	-	0.57	-	-
Se	0.11	-	-	0.07	-	-	0.12	-	-	0.11	-	-
<i>Other parameters</i>												
Crude Protein (g kg <sup>-1</sup> WW)*	25.23	18.58	9.63	24.12	20.81	10.92	26.35	23.94	11.29	27.09	37.94	9.98
Conductivity (mS cm <sup>-1</sup> )	9.7	-	-	1.3	-	-	14.1	-	-	14.6	-	-
Total dissolved salts (g l <sup>-1</sup> )**	7.76	-	-	1.04	-	-	11.28	-	-	11.68	-	-
COD (g l <sup>-1</sup> )	-	96.48	-	-	197.93	-	-	66.09	-	-	68.67	-
Turbidity (NTU)	-	2435	-	-	8015	-	-	1255	-	-	1235	-
Alkalinity (g CaCO <sub>3</sub> kg <sup>-1</sup> WW)	16.1	8.53	39.41	11.6	5.61	16.99	16.9	8.65	34.99	16.7	9.08	39.39
TAN (g NH <sub>3</sub> -N kg <sup>-1</sup> WW)	1.40	1.25	1.85	0.80	0.55	0.85	2.09	1.56	1.90	1.98	1.63	2.04

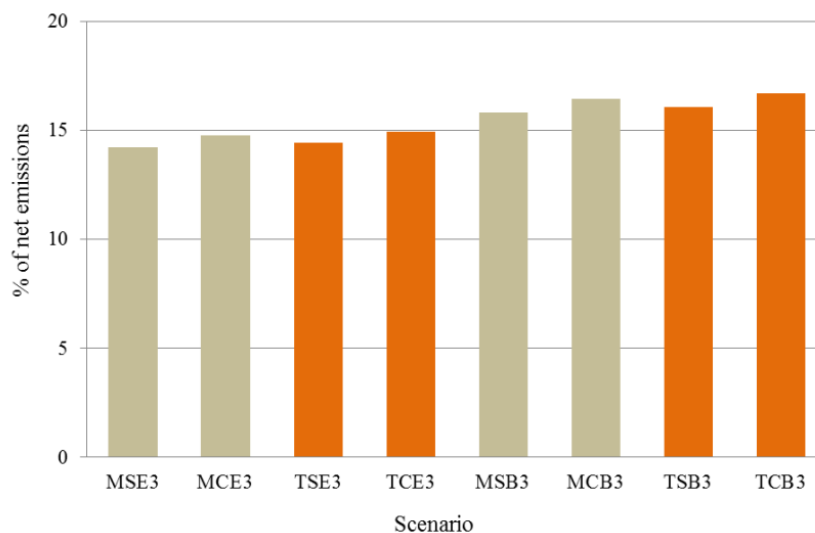
Note: WD = whole digestate, SL = separated liquid, SF = separated fibre,

\* = TKN x 6.25, OLR is expressed in g VS l<sup>-1</sup> day<sup>-1</sup>,

\*\* TDS = k<sub>e</sub>EC, where k<sub>e</sub> is a conductivity factor ranging from 0.55 - 0.8 (0.55 for natural water, 0.65 for hard/alkaline water, and 0.8 for inorganic nutrients), while EC is the electrical conductivity in μS cm<sup>-1</sup> at 25 °C. For the purposes of the calculation, a factor of 0.8 is selected.



**Figure 2.** System boundary for the energy balance analysis on AD of SBP



**Figure 3.** Mineral N fertilizer replacement as % of net GHG emissions savings. The scenarios were identified in the following codes: M= mesophilic, T= thermophilic, S= simple system, C= complex system, E= biogas used in CHP unit for electricity and heat generation, B= biogas upgrading to biomethane. Unless specified, all loading rates are  $3 \text{ kg VS m}^{-3} \text{ day}^{-1}$

#### 4. Conclusion

SBP is a very promising feedstock for AD either at batch and semi-continuous condition. Digestates from mesophilic and thermophilic AD of SBP are potential to be utilised on agricultural and arable land due to its high nutrient and low PTE. Implementation of AD treating SBP can provide economic savings and environmental-friendly performance. Therefore, AD can be used for supporting the circular economy through energy, nutrient, and biofertiliser production from biomass and organic waste.

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