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Identification and Characterization of Potential Feedstock for Biogas Production in South Africa

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ABSTRACT

Biogas is produced during anaerobic digestion (AD) of biodegradable organic materials and is considered a promising renewable energy resource. Feedstocks are essential to ensure the successful anaerobic digestion in biogas digesters. Therefore, the search of appropriate substrates has come into focus. In this study, we examined the potential substrates that could be used as feedstock for the successful operation of an anaerobic digester. The approach used in this study was to identify the potential feedstocks that can be converted into value-added products. The identification of the feedstocks was done based on classification and evaluation of the theoretical biogas and methane production during the digestion process. The results show that all the considered substrates exhibited the biogas theoretical yield, with cattle manure producing the highest yield (0.999 m^3/kg VS), whereas the lowest biogas yield (0.949 m^3/kg VS) was obtained from cassava peels. It was concluded that the use of cassava co-digested with fruit and vegetable waste as an alternative feedstock offers a greater potential in terms of biogas production and could thus be implemented in the biogas projects running with cow dungs inside South Africa, especially in rural communities.

Keywords: Cassava, fruit and vegetable, anaerobic co-digestion, biogas, methane theoretical production

INTRODUCTION

The clamour for the reduction of GHGs and the need for sustainable energy and environment has increased the research efforts into alternative fuels from renewable energy sources, including the bioresources (Achinas et al., 2017). Studies have suggested that in order to ensure the sustainability of future energy needs, more research efforts should focus on renewable energy. Furthermore, the demand for energy is rapidly increasing, with approximately 88% of the world energy based on fossil fuels (Heubaum and Biermann, 2015). Conventional fuel sources, such as coal, crude oil and natural gas are not found in commercial quantities throughout the world. This has left many countries to be energy-dependent on the countries with abundant resources. Political instability of the regions with commercially abundant oil and gas may translate to the insecurity of energy supply in many countries that import these products. Since human and animal wastes are available in every part of the world, biogas (extracted from biomass) will play a critical role for the future in energy (Achinas et al., 2017). Biogas, which is produced through anaerobic digestion (AD), has proven to offer a major advantage of being environmentally friendly and energy efficient, when compared to other forms of energy based on the AD technology (Van Foreest, 2012, Achinas et al., 2017).

The sustainability of AD processes depends on the availability and supply of substrates. Therefore, the identification and quantification of potential feedstock material input is of great importance (Gogela et al., 2017). Without enough suitable material as feedstock, the process of anaerobic digestion will be impractical. Selecting a suitable potential material is the starting point in the process design. Additionally, accurate preparation and use of the feedstock is vital for the biogas digester to run effectively and at its maximum potential (Goemans, 2017). Generally, all kinds of biomass can be used as substrates for the biogas production, as long as they have proteins, cellulose, carbohydrates, fats and hemicellulose (Bond and Templeton, 2011). However, depending on the organic content, the amount and quality of methane produced differ from one feedstock to another (Hagos et al., 2017). The methane content in the biogas indicates the energy value of the biogas; therefore, the quality of a selected feedstock plays an important role in terms of the biogas produced. Low biogas production may indicate low methane content which signifies low energy value (Nnfcc, 2016). For example, according to Dussadee et al. (2016), maize produces more methane in biogas per m^3 than livestock manure, while livestock manure produces greater methane content as compared to human sewage.

The classification and selection of biomass can help in the construction of a database to determine the biogas yield and the rate at which the biogas is produced. Certain factors should be considered to select a viable feedstock. These include:

1. The feedstock should be available in sufficient quantities for the biogas plant to be feasible for a 10 to 20 year lifespan (Nnfcc, 2016)
2. The feedstock should have a sufficient potential to add value (Jordaan, 2018).
3. Fresh and of certain moisture content. Feedstock left in the sun for too long could be rendered unusable due to the loss in the moisture content (Nnfcc, 2016, Dussadee et al., 2016)
4. The carbohydrate content of the feedstock should be within the acceptable range (Jørgensen, 2009) for biogas optimum production or else co-digestion should be considered. It has been reported that if the feedstock mainly consists of carbohydrates such as cellulose and hemicellulose, the methane yield will be low (Sridevi et al., 2012).
5. The feedstock should have passed the theoretical methane production potential test (Biswas et al., 2007).

Need for biogas development in South Africa

There is significant prospect for the biogas production (biomass from agricultural activities) for the generation of electricity in South Africa. At present, the South Africa's daily load profile indicates that peak demands occur between 7a.m.–10 a.m. and 6.p.m.–8 p.m. This is because many South African households use electricity for cooking, as well as for heating (specifically during winter) in contrast to the use of gas which is prevalent in Europe and Unites states of America. As a result, there is disparity in efficiently matching the period of peak demand with the period when the peak solar irradiation is available to produce energy. Similarly, the wind energy profiles usually do not strongly correlate with this demand profile. Due to the fact that biogas plant can be easily located anywhere the feedstock is accessible, it offers a promising alternative for satisfying some part of the load demand in South Africa. The biogas application for electricity generation is specifically appropriate for the rural communities in South Africa, where the feedstock is readily available. As long as a suitable and adequate quantity of feedstock is supplied into the bio-digester, the inadequacies of meeting peak demand in relation to the available power is eliminated, and as such, electricity can be generated at any time of the day and when needed. In essence, it can be used in meeting the peak energy demand spikes.

The benefits of biogas-driven combined heat and power (CHP) plants outstrip the simple production of heat and power. The prospect for the enhancement of human welfare is important. When adopted for rural electrification, heat, gas for cooking or a combination of these can reduce air pollution, improve lighting and contribute to establishing job opportunities for the locals (Owusu and Asumadu-Sarkodie, 2016). A renewable Independent Power Producer (IPP) procurement programme in South Africa has a target of ensuring the installation of 3725 MW of renewable energy to increase the renewable energy penetration in the national energy mix by 2030 (Assessment, 2012). Interestingly, biogas is one of the renewable energy sources incorporated into the 3725 MW of renewable allocation. It is estimated that about 12.5 MW of power will be generated through biogas. However, the development and installation of biogas plant in South Africa has been slow with only about 150 biogas digesters in operation at present. Only few of the existing large scale biogas digesters available in South Africa are majorly used for solid and hazardous waste from landfills, which is in contrast to other developed countries where many more types of feedstock are utilised for larger scale biogas digester (Goemans, 2017). In order to ensure the adoption of biogas in South Africa, it is essential to carry out a preliminary identification and classification of potential feedstock. This will foster the development of a feedstock database, which can help in the placement of biogas digesters across the country. Therefore, this paper presents the identification and characterization of potential feedstock for biogas production in South Africa. Additionally, it explores the preliminary calculation of the theoretical biogas and methane yield of the identified feedstock. This theoretical yield calculation is based on the physical-chemical characterization.

Biogas feedstock and the South African perspective

According to Bond and Templeton (2011), the biomass that contains carbohydrates, proteins, fats, cellulose, and hemicellulose as main components can be used as the feedstock for biogas production. However, certain factors such as the chemical and physical form of the biomass affect the biodegradability of the feedstock (Lee, 2007). Several types of feedstock have been reported for the production of biogas. These include; agricultural wastes, energy crops, municipal bio-wastes, industrial wastes and wastewater (Figure 1) (Steffen et al., 1998). These are further categorized as agricultural-, industrial- and community-based (Table 1).

The industrial waste includes the peels of vegetables, stale cooked and uncooked food. Domestic waste is an underexploited substrate for the production of biogas (Rajendran et al., 2012). The vegetable waste has a high sugar content that easily ferments to organic acids. This encourages acidification that results in the inhibition of methanogenic bacteria activities (Scano et al., 2014). In an effort to enhance the production of biogas, co-digestion of domestic waste and another feedstock is recommended. Raw vegetable should be treated physically by chopping them, as methane production is increased by reducing the particle size due to the increase in surface area for microbial activities (Wantanee, 2004). Biogas can be produced from all organic materials; however, not all of the organic materials are relevant to the South African industry.

Several studies have been conducted using typical feedstock animal waste, human excrements/sewage, kitchen/food waste and co-digestion of multiple feedstock for biogas production. Table 1 shows typical biogas production potential of some of the feedstock used for domestic bio digesters.

MATERIALS AND METHODS

Potential feedstock available in South Africa for biogas

As much as municipal solid waste and sewage are considered the highest potential feedstock in South Africa, other agricultural feedstock could be explored for more opportunities. Table 2 shows some of the potential feedstock that can be explored in South Africa. South Africa has different temperate zones and these different temperatures enhance the production of fruit, with different

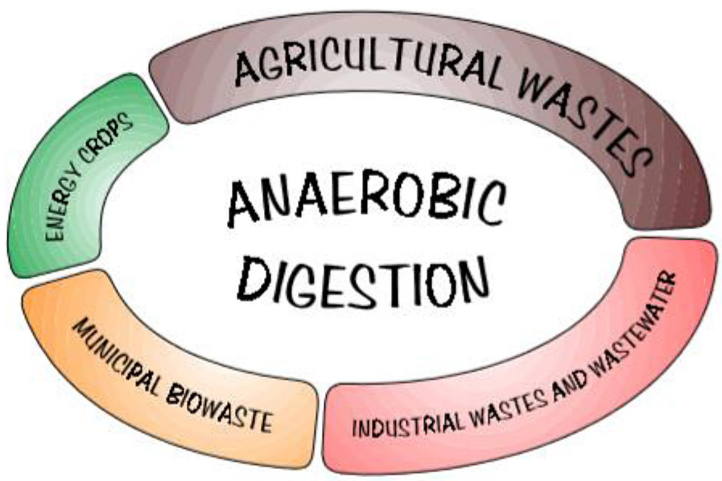

Figure 1. Sources of suitable substrates for anaerobic digestion

Table 1: Various feedstock from different source (Smith et al., 2011)

Sources	Various Feedstock
Agriculture	• Manure • Energy Crops • Algal Biomass • Harvest remains
Industry	• Food/beverage processing • Dairy • Starch industry • Sugar industry • Pharmaceutical industry • Cosmetic industry • Biochemical industry • Pulp and paper • Slaughterhouse/rendering plant
Communities	• OFMSW • MSW • sewage sludge • grass clippings/garden waste • food remains

varieties distributed throughout the country. The major fruit production corresponds to citrus fruits with 2.1 tonnes, which is followed by grapes with more than 1.8 tonnes. These fruits can serve as potential feedstock.

Energy crops, such as cassava, are considered to be a traditional agricultural crop grown normally for food. However, due to its high energy characteristics, it has been considered for energy production (López-Bellido et al., 2014). Cassava – co-digested with other feedstock types – could be an alternative substrate for various communities for the production of biogas in South Africa. Since it is yet to be listed as a staple in South Arica, cassava, its peels and other by-products from its processing can be suitable for energy production.

Identification of energy crop and bio-waste substrates in Southern Africa

Different feedstock types were collected from various sampling procedures. Three (3) different substrates (i.e. cassava tuber, cassava peels, fruits and vegetables and cattle dung) were selected because of their unique properties and their importance in the production of renewable energy through anaerobic digestion. The selected feedstock was collected as follows: cassava samples were collected from a cassava plantation in the Nampula province of Mozambique. Cattle dung was collected from the Ukulinga Research Farm, Pietermaritzburg, South Africa. Fresh fruit and vegetable residues were obtained from a fruit and vegetable supermarket in Pietermaritzburg, KwaZulu-Natal.

Table 3 shows numerous studies conducted on the wastes from the South African fruit industry with regard to waste treatment and beneficiation. Various studies on beneficiation and the application of fruit waste as a feedstock for renewable energy generation has been conducted in South Africa, but co-digestion with other feedstock such as energy crop has been limited. Hence, there is the need to explore this research gap.

Justification of using cattle manure, cassava and fruits and vegetables as co-substrate

It is worth noting that cattle manure, cassava and fruits and vegetables as co-substrate were selected based on the availability and in terms of quantity and the energy production potential. According to Faostat (2018), in 2016, the production of cattle manure is around 136 161 tons per year in South Africa. These large volumes of cattle manure most times end up in landfills or being applied as fertilizer. The use of cattle manure for biogas production provides an alternative option for energy production and waste treatment (Abubakar and Ismail, 2012, Scholtz et al., 2013).

Furthermore, according to Hamilton (2014), cattle manure is rich in organic materials and in nutrients; for this reason it is often used as an agricultural fertilizer. Several studies on the

Table 2: Biogas production from selected feedstock

Feedstock	Daily production (kg/animal)	%DM	Biogas yield (m^3/kg DM)	Biogas yield (m^3/animal/day)	Reference
Cow Manure	8	16	0.2 – 0.3	0.32	(Bond and Templeton, 2011)
Human excreta	0.5	20	0.35 – 0.8	0.04	
Pig Manure	2	17	0.25 – 0.5	0.128	(Surendra et al., 2014)
Chicken Manure	0.08	25	0.35 – 0.8	0.01	
Food Waste	-	34	0.55	-	
Cow Manure: Human excreta (1:1)	-	18	0.407	-	
Food waste: Human excreta (1:1)	-	27	0.489	-	

Table 3: Production volume of feedstock in South Africa (Faostat, 2018)

Group	Feedstock	Total production (Tonnes)
Agriculture	Bananas	371 385.00
	Citrus fruits	2 102 618.00
	Grapes	1 839 030.00
	Apples	790 636.00
	Cassava	Insignificant
	Sugarcane	15 074 610.00
Industry	Fruits and vegetables	1387.00

production of biogas from cattle manure have been conducted by mixing the cattle manure with other organic waste such as households and industrial waste (Maamri and Amrani, 2014, Yohaness). The co-digestion of cow/cattle manure has shown to play an important role in the anaerobic digestion process which has resulted in serval environmental and economic benefits (Hassan et al., 2015). Girija et al. (2013) conducted an analysis on the microbiota of cattle manure. This research analysis indicated that the following bacteria were found in the cattle manure Bacteroidetes (38.3%), Firmicutes (29.8%), Proteobacteria (21.3%) and Verrucommicrobia (2%). These bacteria are responsible for the degradation of complex organic matter in the form of lignocelluloses, chitin, cellulose, xylose and xylem (Martens et al., 2009). For this reason, the use of cattle manure is justified as inoculum and also as co-digester in the anaerobic process.

The production of cassava in the world is about 263 million tons per annum, with South Africa having an insignificant data on the production and consumption available (Faostat, 2018). While cassava has had a long history in the rest of Africa, it is not a well-known crop in South Africa because it is not yet considered a stable food in the country. It will therefore be interesting to explore its energy production potentials in South Africa. Cassava usually survives and produces better harvests in the locations where maize and other energy crops will not grow or yield bountifully. It is drought tolerant and can survive in extreme weather, climatic conditions and soil with low nutrients. Since cassava succeeds under drought conditions, it therefore requires low agro-chemical inputs (Okudoh et al., 2014). However, it yields well to irrigation or in the regions with higher rainfall. Cassava is extremely flexible in its management requirements, and has the potential of high-energy production per unit area of land. Because cassava has no definite maturation point, harvesting may be delayed until market, processing or other conditions are more favorable. This flexibility means cassava may be field stored for several months or more. On the basis of these features, the growth and survival of cassava is guaranteed in South Africa if adequate resources are invested.

Since cassava can both serve as energy crop and food, the use of its peel (waste) instead of the peeled tuber (food) is suggested in this study. Alternatively, energy crops can be grown on marginal land (landfills) as a capping for landfill (Figure 2), therefore making the crop unsuitable for food crop production. The latter is proposed here due to the fact that in South Africa, some landfills are at the stage of being decommissioned. This creates the land for the capping of landfill through the use of cassava. Though the

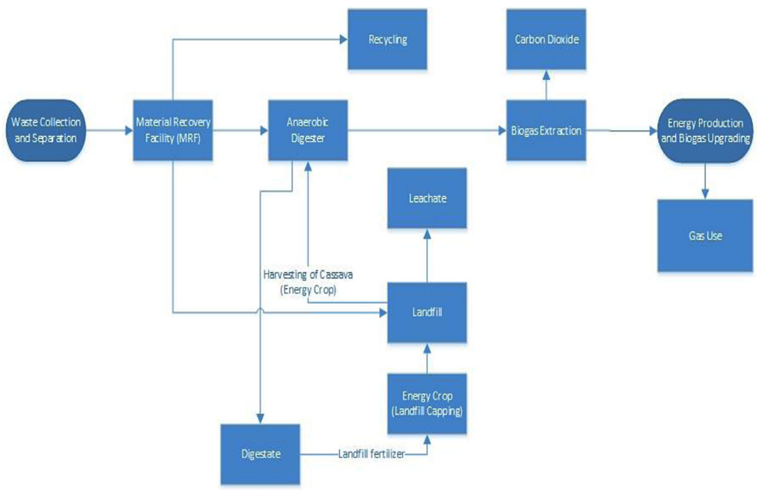

Figure 2. Integration of energy crops and waste into landfill operation for biogas production

production of cassava is lacking in South Africa, using cassava as a capping crop for landfill would enable its application for energy generation after harvesting. This is because the landfill capping crop has low biodiversity and economic value as there is a high risk of the cassava absorbing toxic trace elements that could present health risks for humans (Whiting et al., 2004, Hutchings et al., 2001). The cassava biomass has many benefits, since it contains large amount of fermentable sugar (Okudoh et al., 2014).

METHOD FOR SAMPLING, PREPARATION AND CHARACTERIZATION OF FEEDSTOCK

Sampling method and preparation of feedstock

In an effort to obtain a more homogenous sample, the substrates were thoroughly mixed, after which each pile was divided into four parts. Two diagonally opposite quarters were mixed, while the other two diagonally opposite quarters were removed or discarded (Figure 3). The mixed diagonals were again divided into four parts. This procedure was repeated until a small sample has been extracted. The above-mentioned procedure was followed for all the substrates.

The preparation of the potential feedstock was performed following the outline protocol below:

Cassava

The cassava samples were collected in such a way that it covered random different parts of the entire volume. These sub-samples were mixed together. Coning and quartering were used to reduce the size of the mixed samples. One hundred kilograms of the collected fresh cassava tuber was mechanically pre-treated by peeling, while the remaining 100 kg of the fresh cassava was not peeled. Both the peeled and unpeeled cassava were washed with tap water with a pH of 7 and chopped into pieces of about 1 cm^3. Thereafter, it was dried in sunlight for two days (Figure 3). All prepared feedstocks were stored in a refrigerator at 4˚C. The dried cassava tuber was milled with a scientific RSA hammer mill that is equipped with a 2 mm sieve mesh to obtain the cassava flour. This is because smaller particles do not only increase biogas production rate, but also affect the hydraulic retention rate (Mshandete et al., 2006, Karp et al., 2013).

Cattle dung

Fresh cattle dung (CD) was mixed with water (W) to a ratio of 1:2 To to form a cattle dung slurry, (CD:W) (Biswas et al., 2011). The slurry inoculum was filtered by passing it through a 0.5 mm diameter sieve to separate the solid content from the slurry, after which it was kept in a container at 4°C.

Fruit and vegetable residue

Fresh fruit and vegetable residues were sampled randomly. The samples were then oven-dried at 60°C until they reached a constant weight. The sample size was reduced to <1 mm through milling. The equipment combination of a TRF 400 hammer mill and a laboratory blender were used for size reduction. The fruits used in this experiment were mainly banana, which were analysed as the fruit only (peeled banana). The sample was stored in plastic sample bags in the refrigerator at 4°C before analysis. This was to ensure that the condition of feedstock remained unchanged to avoid obtaining flawed results (Assegid and Kebede, 2014).

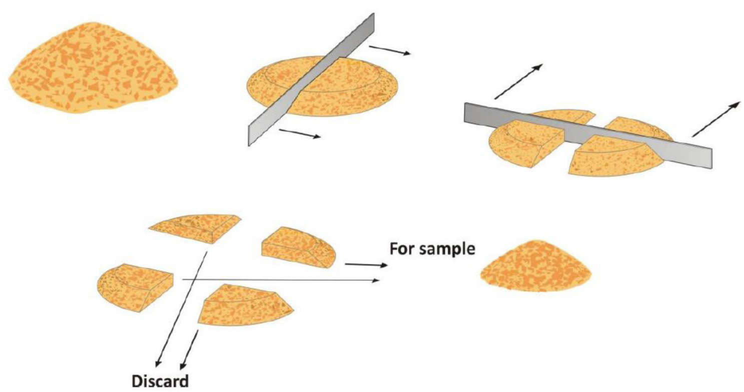

Figure 3. The coning and quartering method (Alakangas, 2015)

Feedstock composition and physicochemical characterization

The feedstock sample was characterized in terms of the proximate and ultimate analysis. The proximate analysis refers to the physiochemical features in terms of its moisture content, total solids, volatile solid, pH value, total nitrogen, total carbon and ash. In turn, the ultimate analysis refers to the elemental carbon (C), hydrogen (H), nitrogen (N), oxygen (O), and sulphur (S) compositions in the feedstock under consideration. The main purpose for conducting the characterization tests is to determine and understand the physical and chemical characteristics of the substrates that are being used, thereby creating a reference point for the experiments. This will assist in assessing how effective the substrate is in the production of biogas.

The analyses were conducted on the individual feedstock (cassava tuber, cassava peel, fruits and vegetable and cattle dung) using the American Standard Methods for Examination of Water and Wastewater (ASTM). The tests were repeated in triplicate for accuracy and repeatability (Eaton et al., 2005)

Moisture content (MC)

The ratio of the mass of water to the total mass of the sample is defined as moisture content. MC can be illustrated by the following Equation 1:

$$MC(\%) = \frac{Massofwetsample - Massofdrysample}{Massofwetsample} x100 \quad (1)$$

The procedure used to measure the moisture content was as follows: approximately 100 g of solid sample (each substrate) was weighed into crucibles at room temperature, after which it was placed into the oven at 105°C for 24 hours. Thereafter, the heated samples were placed in desiccators to cool down. The desiccator contains silica gel underneath as illustrated in Figure 4. The silica gel inside the desiccators absorbed any moisture that was present. The desiccators were moisture free. After cooling down the sample to obtain the mass of the dry sample, the cooled down sample was weighed again. Afterwards, the moisture content was calculated using Equation 1.

Total solids(TS)

Total solids (TS) is the measurement that represents the quantity of total solid residue that remains after the sample has been oven dried at 105°C for 24 hours. The test was conducted in accordance with the Standard Method for the Examination of Wastewater by Eaton *et al.* (2005) no. 2540 G, D and it is calculated using Equation 2.

$$TotalSolids(\%) = \frac{Massofdrysample}{Massoftotalsample} x100 \quad (2)$$

Volatile solids (VS)

The residue from the TS test was placed in the furnace (Figure 5), which was fired at 550°C for 2 hours to calculate the VS. Before placing the residue in the furnace, it was pre-heated to 550°C. The total VS test was used to determine the quantity of organic matter in the sample (Eaton *et al.*, 2005). The tests were conducted in accordance with the Standard Method of Examination of

Figure 4. (a) Crucibles in oven at 105°C, (b) Crucibles in desiccator to cool down

Wastewater and Water-no. 2540 G (Eaton *et al.*, 2005) and the total Volatile Solids were calculated using Equation 3.

$$TotalVolatileSolids(\%) = = \frac{Massofdrysample - Massofsamplefired \in furnace}{Massoftotalsample} x100 \quad (3)$$

pH

The acidity or alkalinity in a solution was measured by a pH test. The test was conducted in the slurry before the use of the substrate for anaerobic digestion using a Labotec Orion Model 410A pH metre as illustrated in Figure 6. The measurement of the pH of the substrate is essential to determine if the pH level of the substrate is within the required range for the production of biogas. Before using the pH metre, it was first calibrated to a pH range of 4–10. The probe was dipped into the sample to obtain the pH readings.

Mathematical models for determination of theoretical methane production

According to Labatut et al. (2011), there are several theoretical approaches to estimating the Biochemical Methane Potential (BMP) of a feedstock or substrate. This is based on the assumption that the substrate will completely degrade and that the microorganisms in the substrate do not use energy (Forgács, 2012). This method relies on the accuracy of the data of substrate composition; therefore, it cannot represent a realistic representation of BMP which is often higher than that of the observed methane (Forgács, 2012, Labatut et al., 2011). Some of the theoretical BMP used to estimate the maximum methane are as follows:

Elemental composition: if the elemental composition (ultimate analysis) of the waste material/substrate is known,

Substrate nutrient composition: assuming the organic waste comprises of carbohydrates, proteins and lipids.

Theoretical methane production potential from substrate elemental composition

The ultimate analysis results of the selected feedstock are presented in Tables 5 & 6. The elemental composition was used, according to Franco et al. (2007), to estimate the maximum theoretical biogas and methane yield using the Buswell's equation to calculate the theoretical methane yield (Buswell and Neave, 1930). The general molecular formula can be presented to be of the form

$$C_aH_bO_cN_d + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right) \rightarrow$$

$$\rightarrow \left(\frac{4a + b - 2c - 3d}{8}\right) CH_4 \cdot \quad (4)$$

$$CH_4 + \left(\frac{4a - b + 2c + 3d}{8}\right) CO_2 + dNH_3$$

Equation 5 above represents the degradation of carbon in the substrate under consideration. The coefficients a, b, c, and d are dimensionless and can be evaluated from the approximated ratio of each component number of moles to the minimum number of moles among all the components

Figure 5. Crucibles in furnace at 550°C

Figure 6. Orion Model 410A pH metre

(Roati et al., 2012, Jingura and Kamusoko, 2017), where:

$$a = \frac{\frac{\%C}{MolarMassC}}{L},\ b = \frac{\frac{\%H}{MolarMassH}}{L},$$

$$c = \frac{\frac{\%O}{MolarMassO}}{L},\ d = \frac{\frac{\%N}{MolarMassN}}{L}, \quad (5)$$

$$\text{and } L = \frac{\%M}{MolarMassM}$$

where: %C, %H, %O and %N represent the composition of C, H, O and N in the organic substrate respectively.

M represents the element with the minimum number of moles in a given sample, and in most cases, M is usually nitrogen, such that the value of d is almost always equal to 1. Molar Mass C is the molar mass of carbon, and the same applies for hydrogen (H), oxygen (O) and nitrogen (N).

The maximum theoretical biogas production (B_{th}) and the theoretical methane production (M_{th}) can be estimated from Equations 6 and 7, respectively.

$$B_{th}\left[\frac{m^3}{kg_{vs}}\right] = \frac{a22.415}{12a + b + 16c + 14d} \quad (6)$$

$$M_{th}\left[\frac{m^3}{kg_{vs}}\right] = \frac{\left(\frac{4a + b - 2c - 3d}{8}\right)22.415}{12a + b + 16c + 14d} \quad (7)$$

The Buswell equation (Roati et al., 2012) was further used to verify the selected promising substrates for further examination in the laboratory and in a pilot scale test.

RESULTS AND DISCUSSION

Identified biogas production biomass

Cassava tuber, cassava peels, cattle dung, fruits and vegetable residues were selected for this study. Figure 7 (A – E) shows pictures of selected biomass for this study.

Proximate and ultimate analysis results

Table 4 shows the results of proximate and ultimate analysis of all the selected feedstock for anaerobic digestion. All the feedstocks (cassava tuber, cassava peels, fruits & vegetables and cattle dung) were characterized and the results show some differences in most of the properties as shown in Table 4.

The Table 4 above indicates a major difference in the moisture content with cattle dung having the most moisture content at 83.50%. The cassava peels showed lower starch content (61%) compared to that of the cassava tuber with 76%. However, the cassava peels reported a higher fermentable sugar of 79%, which is higher than that of the cassava tubers by 1.5%.

The cassava peel showed high traces of heavy metals, namely Zn, Mn and Fe (25.10 mg/kg, 36.45 mg/kg and 201.09 mg/kg) compared to that of cassava tuber. According to Hoban and Berg (1979), traces of Fe is essential to the fermentation of methane.

The carbon-to-nitrogen ratio of a feedstock is represented by C/N. The C/N ratio among other factors plays an important role for a feedstock to produce optimal gas. A feedstock with a ratio 25:1 of C/N produces an optimum gas (Gerardi, 2003). According to Kwietniewska and Tys (2014), for optimum performance of the AD the feedstock should have a C/N ratio of 20:1 – 30:1. It can be observed that all the selected feedstock types have a C/N ratio of greater than 30:1, which could cause rapid depletion of nitrogen and as a result cause lower production of gas (Khalid et al., 2011), with the exception of cattle dung, which is within the range. In order to mitigate the C/N ratio outside of the range, co-digestion could be considered (Hartmann et al., 2002). However, the correct combination of other parameters (pH, biodegradable organic matter and toxic compounds) in the co-substrate mixture is important. Increasing the biogas yield co-substrates in the digester with carbon rich substrates such as energy crop would be favourable (Pavan et al., 2007). Cassava tuber and cassava peels were found to be rich in carbohydrates with sugar content of approximately 78%, which is a good indication of cassava potential as it is well-recorded that high biogas yields are usually related to the high carbohydrate (Achinas et al., 2017). Carbohydrates in cattle manure could not be determined due to complexity, as the substrate is composed of carbohydrates, proteins and fats, while the carbohydrates in fruits and vegetables largely contain carbohydrates and a relatively lesser amount of proteins and fats.

According to Christy et al. (2014), the different stages of the AD process require different

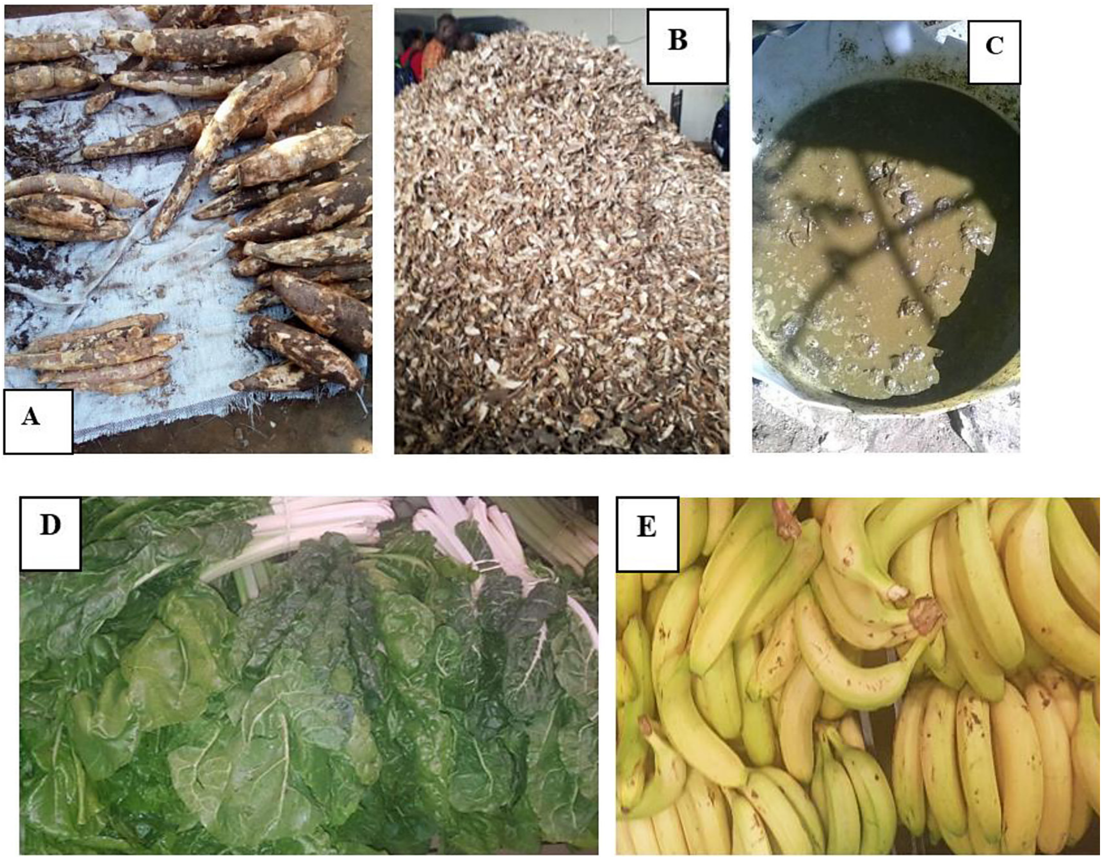

Figure 7. (A) Unpeeled cassava tuber, (B) Cassava peel, (C) Cattle dung, (D) Vegetable and (E) Fruit

Table 4. Various studies on fruit waste in South Africa

Study focus	Fruit waste	Outcomes	References
Bioremediation and beneficiation application	Pineapple cannery wastewater	Suitable to produce ethanol due to its high carbohydrate content of about 19.8 g/L.	(Prior and Potgieter, 1981, Garcin and Burton, 2007)
Water and wastewater management in fruit- and vegetable-processing plants	Fruits and vegetables	Guideline to minimise water intake and wastage	(Khan et al., 2015)
Renewable energy	Fruit cannery wastewater	The anaerobic digestion of fruit cannery wastewater for biogas production through the use of an upflow bioreactor.	(Sigge and Britz, 2007)
Renewable energy	Various fruit processing Wastes	Potential Energy recovery from fruit waste identified theoretically	(Burton et al., 2009)

ND: Not determined

optimal pH value (Hydrolysis Stage – pH 4, Acidogenisis Stage – pH 6.5, Acetogensis stage – pH 6.0 and Methanogenesis stage – pH 6.5–7.8). The selected substrates (Table 4) have a pH within the acceptable range of 6.5 and 7.8 for the AD process to perform well (Okonkwo et al., 2013). Cattle manure is an easy choice of feedstock because of its neutral pH and its resistance to a change in pH. However, it has low energy because of its pre-digestion in the gastrointestinal (Meshach, 2013).

Theoretical methane production potential from substrate elemental composition

The ultimate analysis (elemental composition) was performed for all the selected feedstock types (cassava, cattle manure, and fruit & vegetable waste). Equations 6 & 7 were used to estimate the ultimate methane in order to investigate the potential of the feedstock selected. Mono-digestion were conducted, the results obtained are shown in Table 5.

The results in Table 5 show that the cattle manure obtained the highest ultimate methane yield (0.575 m^3/kg VS), whereas the lowest methane yield (0.495 m^3/kg VS) was obtained from cassava peels. This result indicates that the selected feedstock has a potential of producing biogas.

Numerous studies showed that co-digestion is a promising way of improving the performance of AD is the co-digestion (Zhang et al., 2014). The elemental analysis is used to calculate the ultimate methane yield of co-digested substrates at different ratios (Table 6) (Gerber and Span, 2008, Biswas et al., 2007). Table 6 shows that co-digesting CT with F&V improved the biogas and methane yield which is in agreement with the literature, which indicates that improvement of biogas yield could be done by co-digestion of two or more substrates at the correct ratio. This may assist in establishing the methane potential of the substrate at different substrate ratio which can thereafter be investigated further through experimental process.

CONCLUSION

This paper presents the identification and characterization of potential feedstock for biogas production in South Africa. Using American Standard Methods for Examination of Water and Wastewater (ASTM) method, the pH, total solids (TS), volatile solids (VS), total carbon and total nitrogen were determined that is proximate and ultimate analysis of the feedstocks. The conclusions drawn from the results obtained are as follows:

1. The large amount of carbohydrate, total solids (TS), volatile solid (VS) and the low fibre in the cassava biomass indicates a high biogas production potential. However, the carbon to nitrogen ratio (C:N) of cassava tuber and cassava peels, amounting to 74.84:1 and 59.67:1, respectively, is higher than normal and may have to be co-digested with animal manure such as cattle manure to bring the C:N ratio to about 20:1;

Table 5. Physical and chemical characteristics of cassava tuber, cassava peels, fruit & vegetable waste and cattle dung

Characterization	Biomass			
	Cassava tuber	Cassava peel	Fruit & vegetable waste	Cattle dung
Moisture content (%)	61.58 ± 2.11	79.68 ± 0.01	58.40 ± 0.1	83.50 ± 0.4
Total solids (%)	42.25 ± 1.51	20.32 ± 0.12	41.60 ± 1.2	19.84 ± 0.3
Volatile solids (%)	91.27 ± 0.52	75.51 ± 1.01	76.10 ± 0.3	12.40 ± 1.5
Starch (%)	76.32 ± 2.01	61.42 ± 0.21	ND	ND
Sugars	77.54 ± 1.11	78.74 ± 1.07	42.87 ± 1.01	ND
pH	6.87 ± 0.47	6.94 ± 0.24	7.34 ± 0.15	6.57 ± 0.11
Protein (g)	1.01 ± 0.01	1.11 ± 0.11	77.30 ± 0.67	-
Total nitrogen (%)	0.53 ± 0.44	0.87 ± 0.14	0.52 ± 0.34	2.06 ± 0.2
Total carbon (%)	39.67 ± 1.78	51.91 ± 0.01	39.06 ± 0.11	43.12 ± 0.7
C:N	74.84:1	59.67:1	75.12:1	18.50:1
Ash (%)	3.06 ± 0.66	4.98 ± 0.31	9.44 ± 0.11	1.66 ± 0.21
Phosphorus (%)	0.16 ± 0.57	0.20 ± 1.21	ND	0.42 ± 0.04
Fe (mg/kg)	62.00 ± 0.17	201.09 ± 0.51	ND	ND
Zn (mg/kg)	15.01 ± 0.12	25.10 ± 1.17	ND	ND
Mn (mg/kg)	8.02 ± 1.21	36.45 ± 0.55	ND	ND

Table 6. Mathematical ultimate methane yield of different substrates using elemental analysis

Sample	Elemental analysis					C, H, O, N coefficients				Molecular formula	$B_{th}\left[\frac{m^3}{kg_{vs}}\right]$	$M_{th}\left[\frac{m^3}{kg_{vs}}\right]$
	pH	N	C	H	O	A	b	c	d			
CP	7.07	0.87	51.91	5.90	41.79	69.61	94.94	42.03	1	$C_{70}H_{95}O_{42}N$	0.965	0.496
CM	6.62	1.38	22.50	3.29	14.90	19.02	33.38	9.45	1	$C_{20}H_{34}O_{10}N$	0.999	0.575
CT	6.62	1.75	53.29	5.93	41.16	35.53	47.44	20.58	1	$C_{31}H_{36}O_{21}N$	0.975	0.499
F & V	6.62	2.17	39.49	5.85	30.16	21.23	37.74	12.16	1	$C_{30}H_{21}O_{12}N$	0.949	0.533

F & V: Fruits and Vegetable waste; CP: Cassava Peel; CT: Cassava Tuber; CM: Cattle Manure

Table 7. Mathematical ultimate methane yield of different co-digestion ratio using elemental analysis

Sample	Elemental analysis					Molecular formula	$B_{th}\left[\frac{m^3}{kg_{vs}}\right]$	$M_{th}\left[\frac{m^3}{kg_{vs}}\right]$
	pH	N	C	H	O			
CM:CP (20:80)	7.07	1.35	52.03	6.26	40.36	$C_{45.01}H_{65.00}O_{26.18}N$	0.971	0.512
CM:CP (40:60)	6.62	1.83	52.39	6.65	39.12	$C_{33.37}H_{50.84}O_{18.69}N$	0.979	0.528
CM:CP (50:50)	6.62	2.07	52.57	6.85	38.51	$C_{29.59}H_{46.23}O_{16.25}N$	0.982	0.536
CM:CP (60:40)	6.62	2.31	52.76	7.04	37.89	$C_{26.59}H_{42.59}O_{14.32}N$	0.985	0.543
CM:CP (80:20)	6.62	2.80	53.12	7.43	36.65	$C_{22.15}H_{37.19}O_{11.46}N$	0.992	0.559
CT:FV (20:80)	7.07	2.58	51.11	7.19	39.13	$C_{23.13}H_{39.03}O_{13.28}N$	0.954	0.526
CT:FV (40:60)	6.62	2.36	51.38	6.84	39.42	$C_{25.38}H_{40.56}O_{14.60}N$	0.960	0.519
CT:FV (50:50)	6.62	2.25	51.51	6.67	39.57	$C_{26.67}H_{41.42}O_{15.36}N$	0.962	0.516
CT:FV (60:40)	6.62	2.14	51.65	6.50	39.71	$C_{28.08}H_{42.39}O_{16.20}N$	0.964	0.512
CT:FV (80:20)	6.62	1.92	51.91	6.15	40.01	$C_{31.39}H_{44.63}O_{18.14}N$	0.970	0.505

F & V: Fruits and Vegetable waste; CP: Cassava Peel; CT: Cassava Tuber; CM: Cattle Manure

2. The benefit of using cassava biomass for future crop-based biogas plants is that it reduces the need to use lands available for food production and artificial fertilizers, as they can be cultivated in degraded lands such as landfills;
3. The analysis of the theoretical methane production potential from substrate elemental composition showed that the highest methane yield was achieved from cattle manure (0.575 m^3/kg VS) while the lowest methane yield (0.495 m^3/kg VS) was obtained from cassava peels.
4. The mathematical ultimate methane yield of fruit and vegetable using elemental analysis showed a much higher methane yield (0.533 m^3/kg VS) compared to cassava tuber and cassava peels, reaching 0.499 m^3/kg VS and 0.496 m^3/kg VS respectively.
5. Thus, this study shows that cassava (tuber and peels) and fruit and vegetable wastes are potential sources for energy production. A further study will focus on ascertaining the biogas yield using the estimated theoretical biogas and methane yield in order to evaluate technical and economic feasibility of the identified substrates through laboratory scale and pilot scale digester.

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