Co-Digestion of Animal Manure and Cassava Peel for Biogas Production in South Africa

Nathaniel Sawyerr, Cristina Trois, Tilahun Workneh and Vincent Okudoh

***Abstract*—** Global energy demand is on the rise due to continuous increases in population, economic growth, and energy usage. Several studies have been done on biogas, but in South Africa, these are biased towards industrial wastewater. Therefore, there is need to explore other alternatives for biogas generation, for example energy crops such as fodder beets and cassava, on which studies are limited. Cassava has several advantages compared to other crops, including the ability to grow on degraded land and where soil fertility is low. It also has the highest yield of carbohydrate per hectare (4.742 kg/carb) apart from sugarcane and sugar beet, which makes it suitable for bioenergy (biogas) generation. This study was designed to determine the performance of co-digestion of cassava peel (CP) with cattle manure (CM) at different ratios, as well as to study the effect of the mixed ratios on methane yield through batch anaerobic digestion. All digesters were run simultaneously under mesophilic temperatures of 35 ± 1 °C. The digestion was carried out in 600 mL SCHOTT DURAN® glass laboratory bottles. The results showed that co-digestion influenced biogas production and methane yield. The final cumulative methane yields by the co-digestion of CM and CP at the CM:CP mixing ratios of 80:20 and 20:80 were 738.76 mL and 838.70 mL, respectively. The corresponding average daily methane yields were 18.42 mL/day and 20.97 mL/day. This indicates that CP enhanced the production of methane in the co-digestion process with the 20:80 CM:CP ratio.

***Keywords*—**Cassava, Biogas, Co-digestion, Biomass, Animal Manure.

I. Introduction

Biogas technology offers a long-term sustainable renewable energy alternative with the potential to address economic, environmental, and social concerns arising from industrial development [1]. Anaerobic fermentation of biomass is a well-developed and efficiently applied process for methane gas production [2, 3] from the recycling of various organic wastes under anaerobic conditions [4, 5]. Feedstock used for biogas production includes plant waste, animal waste, food waste, municipal sewage sludge, and paper waste [5]. Moreover, the quality and quantity of methane yielded and biogas produced largely depends on feedstock characteristics and digester operating conditions including hydraulic retention time, pH, carbon-nitrogen (C/N) ratio, and inoculum [2].

Therefore, improving the efficiency of biogas production also requires improving the characteristics of the feedstock and operating conditions of the digester.It is also well established that the co-digestion of two or more feedstocks produces a higher methane yield than a single feedstock [6, 7]. Co-digestion is the process of mixing two or more substrates and digesting them simultaneously. Some of the major benefits of anaerobic co-digestion over mono-digestion include increased biogas production and methane concentration [8, 9].

Co-digestion has been utilised extensively to improve the efficiency of biogas production. Its efficiency may be influenced by parameters such as nutrients, feedstock pH, temperature, feed flow rate (loading rate), feedstock type, mixture ratio, and retention time. However, these factors may slow or stall the process of biogas production if their values are not within a certain range. Therefore, understanding the importance and optimal operating conditions for each parameter during anaerobic digestion (AD) will contribute to the realization of optimal hydrolyses and digestion [10].

The function of co-digestion during AD includes balancing nutrients (C/N ratio, micro- and macro-nutrients), pH regulation, and dilution of inhibitors/toxic compounds [5, 7, 11]. These highlight the fact that co-digestion could be a simpler method to improve the feedstock characteristics and digester operating conditions. The improvement of biogas production via co-digestion also requires careful selection of feedstocks [11]. In addition, the characteristics and availability of each feedstock plays a key role in improving the efficiency of AD. To improve the efficiency of plant residues in biogas production, co-digestion with a mixture of two or more substrates is considered a more appropriate cost-effective method than pre-treatment. This is because the addition of nitrogen-rich substrates such as animal manure/slurries will help balance the C/N ratio of carbon-rich plant residues [12, 13]. Co-digestion of energy crop residue with a nitrogen-rich substrate will mitigate the rapid acidification of the digester by the high lignin content of plant residue [7]. Furthermore, it will ease the utilisation of energy crops by microorganisms and improve biogas production and methane yield.

Therefore, this study aims to evaluate the co-digestion of cassava peel and cattle manure at different ratios as well as the effect of the mixing ratios on methane yield from AD [14].
The main research highlights of this paper relate to:

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- Collecting data on co-digestion of cassava peel (CP) with cattle manure (CM)
- Comparing data on biogas yield from mono-digestion and co-digestion of feedstock
- Finding that the maximum biogas yield was obtained from the CM: CP co-digestion ratio of 20:30

II. MATERIALS AND METHODS

The study was divided into two stages, namely (i) assessing the mono-digestion and co-digestion of the substrates by testing in biochemical methane potential (BMP) reactors at a mesophilic temperature (36 °C) using CM and CP, and (ii) using mathematical models to determine theoretical methane production using the elemental composition of the feedstock.

A. Collection and Preparation of Substrates for Biogas Production

The substrates tested in the BMP reactors were CM (animal biomass) and CP (plant biomass). The animal biomass used for this study was collected in a large clean plastic container from Ukulinga Research Farm at the University of KwaZulu-Natal, Pietermaritzburg, South Africa, while the energy crop biomass (CP) was imported from Nampula Province, Mozambique, as it is more easily available there compared to in South Africa [15]. The characteristics of the substrates used are presented in Table II.

CPs was prepared from fresh cassava roots, which were peeled mechanically with a sharp knife (Fig. 1A). After this, the CPs (Fig. 1B) were washed thrice in tap water and allowed to drain for about 30 min. Subsequently, the CPs were sun dried for two consecutive days in order to reduce their cyanide content [16]. The CM was homogenized using a hammer mill (SER No. 400, Scientific South African, South Africa) and a laboratory blender to reduce the particle size to less than 5.0 mm (Fig. 1C). The CPs were shredded into smaller sizes. However, about 20 kg of CP was soaked in water for one month at ambient temperature (35 °C) to soften the substrate and ensure that the micro-organisms involved in AD could feed easily on bacteria to produce the biogas. Both the homogenized CM and prepared CP were stored in a refrigerator at 4 °C. The soft CP was made into a slurry by adding water, as shown in Table I. A flowchart indicating the steps used in the process of biogas production from cassava peels is shown in Fig. 2.

Fig. 1: (A) Unpeeled cassava roots, (B) cassava peels, and (C) blended cassava peels

Fresh Cattle Dung (FCD) collected from Ukulinga Research Farm was used as an inoculum to start up the experiment. This was prepared by mixing FCD with deionized water in a 1:1 ratio (100 g cattle dung:100 mL water). The inoculum was kept in an airtight container at 4 °C; prior to use, it was acclimated and degassed at 35 °C for three weeks to minimize the production of methane from the inoculum. The characteristics of the substrates used in this study (i.e. CM and CP) are shown in Table II.

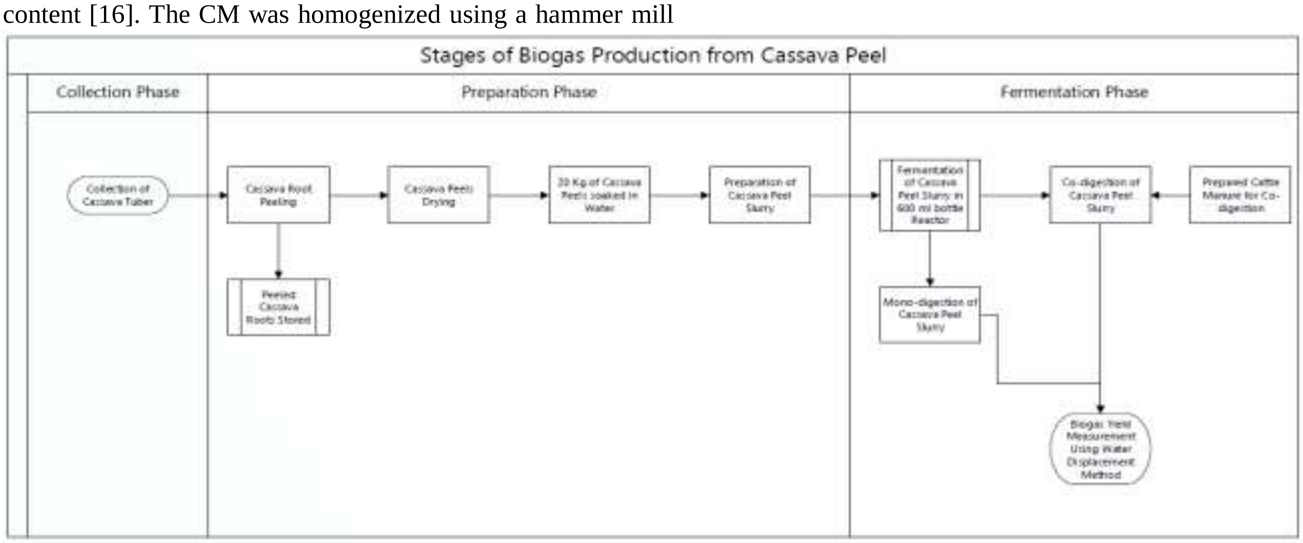

Fig. 2: Flow chart showing the steps used to prepare cassava used for biogas production

B. Experimental Design

The BMP was studied by investigating the co-digestion of CM and CP. Four co-digestion ratios were investigated: CM:CP

= 100:0, CM:CP = 0:100, CM:CP = 80:20, and CM:CP = 20:80. These ratios were based on the volatile solids content, and 1.5 g VS/100 mL of slurry was used in each bottle. Three runs of the experiment were conducted using 600 mL SCHOTT DURAN® laboratory glass bottles as the batch reactor. The experiments were conducted under mesophilic conditions with a temperature of 36 °C. The experimental design shown in Table I was used for all three runs. Substrate and deionised water were added to each reactor bottle to produce an effective solution of 1.5 g VS/100 mL. Organic loading was used to avoid acidification while simultaneously ensuring manageable gas volumes (Hansen et al., 2004). The headspace in all the reactor bottles was kept at 20 mL (working volume of 580 mL) and the bio-digesters were flushed with nitrogen gas to set anaerobic conditions.

An inoculum comprising a mixture of 100 g raw (fresh) cattle dung and 100 mL deionized water was prepared. Additionally, 100 g of the raw CM was mixed with 100 mL of tap water and fed to the same anaerobic bio-digester. The slurry was inoculated with the prepared FCD to a ratio of 1:2 w/w. The same method was used to prepare the CP feedstock. The biogas produced was measured using the displacement method. Then the cumulative biogas volume was calculated and corrected to standard pressure (760 mm Hg) and temperature (0 °C). Sodium hydroxide (NaOH) was put into the inverted displacement bottle to absorb CO2 biogas produced in the reactor, therefore, it can be assumed that the gas collected in the headspace of the inverted displacement bottle was mainly methane, such that the liquid volume displaced and collected in the measuring cylinder indicated the volume of methane produced (Fig. 3). The methane produced was measured daily.

C. Biochemical Methane Potential (BMP) Apparatus Setup

The BMP experiment was carried out in 600 ml SCHOTT DURAN® glass laboratory bottles (bio-digesters) operated in a batch system (Fig. 3). The bio-digester bottles were plugged with tight rubber plugs equipped with valve for biogas measurement. The bio-digester was operated at a controlled temperature of 35 ± 1 °C using a thermostatically controlled electricity heated water bath. The biogas that formed inside the bio-digester was measured using the liquid displacement method as indicated in Fig. 3. The schematic diagram of experimental laboratory was set up as shown in Fig. 3.

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TABLE 1
BIOCHEMICAL METHANE POTENTIAL EXPERIMENTAL DESIGN

Co-digestion	Ratio	Mass of CM (g)	Mass of CP (g)	VS (g)	Solution Volume (mL)	Loading (g VS/100 mL)
CM:CP	100:0	20.11	0	8.7	580	1.5
CM:CP	0:100	0	10.37	8.7	580	1.5
CM:CP	80:20	16.09	2.07	8.7	580	1.5
CM:CP	20:80	4.02	8.29	8.7	580	1.5

D. Analytical Methods

The total solids (TS) and volatile solids (VS) in the feedstocks and inoculum were analysed using standard techniques at the beginning of the AD process and at the end of the 40 d incubation period (APHA, 2005). TS content was determined after drying the sample in an oven overnight at 105 °C. VS content was calculated as TS minus the ash content after ignition at 550 °C in a muffle furnace. The pH levels of the feedstock solutions were measured with a calibrated pH meter (Model 410A, Labotec Orion, South Africa). Daily methane gas production was measured directly as the volume of liquid collected in the measuring cylinders.

E. Data Analysis

Results of all the volume measurements were reported at standard temperature and pressure (STP) (273.15 K,). Daily temperature (T_m) and atmospheric pressure (P_m) were recorded with every measurement of methane volume (V_S). These values were used to calculate the gas volumes at standard conditions (V_{STP}) according to Equation (1) below.

$$V_{STP} = V_s x \frac{T_{STP}}{T_m} x \frac{P_m}{P_{STP}} \quad (1)$$

T_{STP} and P_{STP} represent standard temperature (0 °C) and standard pressure (760 mm Hg), respectively. Daily methane volume was recorded in mL, whereas cumulative methane yield was calculated and standardised to mL CH_4/g VS.

F. Mathematical Models to Determine Theoretical Methane Production

Theoretical Methane production potential from substrate elemental composition

The feedstock used was characterized in order to obtain its elemental composition (Table V). The elemental composition can be used, according to estimate the maximum theoretical biogas and methane yield. Buswell's equation can be used to calculate the theoretical methane yield (Buswell and Neave, 1930). Equation 2 above describes the complete degradation of all the carbon in the substrate. The maximum theoretical biogas production (B_{th}) and the theoretical methane production (M_{th}) can be estimated from Equations 3 and 4 respectively.

$$C_aH_bO_cN_d + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right) H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right) CH_4 + \left(\frac{4a-b+2c+3d}{8}\right) CO_2 + dNH_3 \quad (2)$$

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

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

The Buswell equation can be used to select promising substrates for further examination in the laboratory and in a pilot scale test.

III. RESULTS AND DISCUSSION

A. Characterization of Substrates

Characterization tests were conducted on the substrates and inoculum as presented in Table IV. The substrates were tested for all the compositions shown in Table II below. The CP has high starch content (approximately 61.42%) and is rich in carbohydrates. It has a sugar content of approximately 77%. It also contains approximately 79.68% moisture, 4.98% ash, and 0.2% phosphorus. On the other hand, CM has a moisture content of 69.08%. The C/N ratio of the CP was 45:1, which is considered very high compared to the optimum ratio range of 20–30:1 for maximum biogas yield [15].

TABLE II
CHARACTERISTICS OF FEEDSTOCKS AND INOCULUM

Composition (%)	Substrate		Inoculum (Cattle Dung)
	Cassava Peel (CP)	Cattle Manure (CM)	
Moisture Content	79.68 ± 0.01	69.08 ± 0.15	75.20 ± 0.34
Total Solids	20.32 ± 0.12	30.92 ± 0.12	24.80 ± 0.95
Volatile Solids	75.51 ± 1.01	94.64 ± 4.21	84.67 ± 0.57
Starch	61.42 ± 0.21	ND	ND
Sugar	77,34 ± 0.11	ND	ND
Total Nitrogen	0.87 ± 0.14	1.14 ± 0.05	2.06 ± 1.15
Total Carbon	51.91 ± 0.01	53.95 ± 0.25	35.92 ± 0.17
Ash	4.98 ± 0.31	1.66 ± 0.44	3.80 ± 0.17
Phosphorus	0.20 ± 1.21	0.12 ± 0.73	0.42 ± 0.03

ND = Not Determined

B. pH of Substrate Solution

At the start of the experiment, the pH values of substrate solutions in the BMP batch reactors were measured and recorded. Table III presents the average results for all the runs.

TABLE III:
INITIAL PH VALUES OF SUBSTRATES USED FOR THE BMP

Substrate	pH				STDEV
	Run 1	Run 2	Run 3	Mean	
Cassava (CP)	7.10	7.12	6.98	7.07	0.08
Cattle Manure (CM)	6.51	6.58	6.78	6.62	0.14
Inoculum (Cattle Dung)	6.80	6.55	7.22	6.86	0.34
CM:CP (80:20)	6.53	6.52	6.58	6.54	0.03
CM:CP (20:80)	7.41	7.14	7.34	7.30	0.14

The pH of the feedstock is an important parameter in determining the efficiency of an anaerobic digester. The pH level can drop below 5 during the production of organic acids which occurs during acetogenesis. The optimal pH range for obtaining the highest biogas yield by AD is 6.5–7.5. Table IV shows that the pH of the substrates is within this optimal range. The initial pH of all the substrates ranged from 6.51–7.41 and was within a favourable range; however, during the fermentation process the pH was monitored and measured every five days. To neutralize pH within the bottle reactor, $NaHCO_3$ (10 g/L) was added when necessary.

C. Methane Production

Daily Methane Yield at Different Ratios

The methane production rates under mesophilic conditions for the different mono- and co-digestion ratios, which are based on the average results for daily methane production from the three runs conducted, are presented in Fig. 4. From day 1, all substrates began to produce methane; however, the mixture with the CM:CP ratio of 20:80 produced the highest methane yield of 62.69 mL, followed by the ratio 80:20, with 55.57 mL, 100:0 with 51.19 mL, and 0:100 with 28.80 mL. The high yield of biogas on day 1 could be attributed to the acclimation of the inoculum.

An interesting decrease in the biogas yield, which could have been the result of abatement in methane production caused by acidification in the batch reactors, was observed after day 1; the pH was measured at this stage to confirm the acidification in all batch reactors, and the average results are presented in Table IV. Acidification is expected to occur within the first few days of AD unless a pH control mechanism is instituted.

TABLE IV:
AVERAGE PH ON DAY 2 OF THE BIOCHEMICAL METHANE POTENTIAL TESTS

BMP mixture	pH				STDEV
	Run 1	Run 2	Run 3	Mean	
CM:CP = 100:0	6.12	5.95	5.98	6.02	0.09
CM:CP = 0:100	5.81	5.55	5.78	5.71	0.14
CM:CP = 80:20	5.40	5.48	5.61	5.50	0.11
CM:CP = 20:80	5.55	6.02	5.99	5.85	0.26

After day 7, all reactors began to yield less methane. It was suspected that this abatement in methane production was also caused by acidification in the batch reactors. The co-digestion CM:CP mixture of ratio 20:80 exhausted its methane yield after 38 d, while the other BMP mixtures (CM:CP 100:0, 0:100, and 80:20) did so after 39 d (Fig. 4). The maximum methane yield, 91.05 mL, was produced on day 6 by the CM:CP co-digestion mixture with the ratio 20:80, which otherwise had an average yield of 20.97 mL/day. The other BMP mixtures, that is, with CM:CP ratios of 100:0, 0:100, and 80:20, produced maximum methane yields of 61.42 mL, 38.15, and 52.28 mL respectively. The experiments were stopped at 40 d, when methane production ceased.

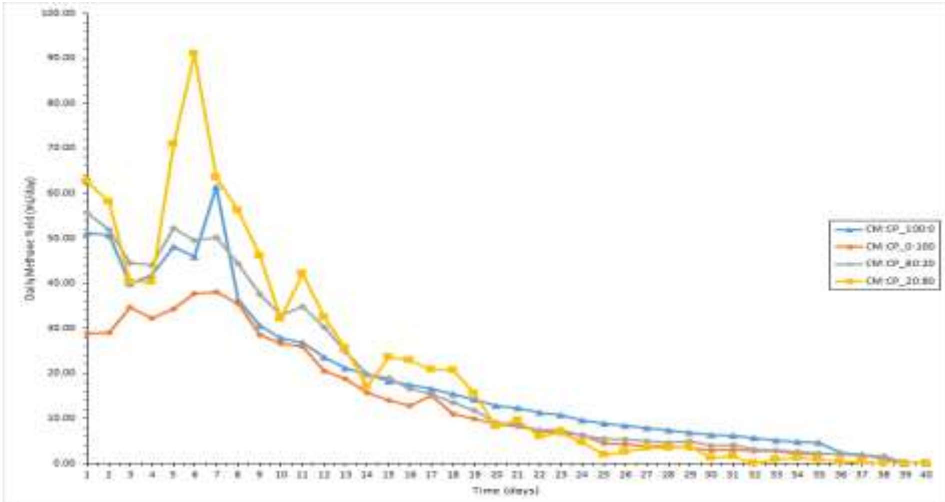

Fig. 3: Daily methane yield, over 40 d, from different ratios of cattle manure (CM) to cassava peel (CP)

D. *Cumulative Methane Yield at Different Ratios*

The cumulative methane yield of the substrates tended to follow the horizontal asymptote representing the maximum methane production per gram of VS (CH4/g VS) achievable from the each substrate. In Fig. 5, the x-axis displays the observation time in days, whereas the corresponding cumulative methane yield, expressed as mL CH4/g VS, is displayed on the y-axis. Mono-digestion at the CM:CP ratio of 0:100 was inhibited, and it had a low cumulative methane yield of 61.75 mL/g VS (Fig. 5), while the highest cumulative methane yield was obtained from co-digestion of CM:CP at a ratio of 20:80 (96.40 mL/g VS) which was higher than that of the other co-digestion processes. The highest cumulative methane yield resulted from the mixing ratio in which the CM provided the nutrients, appropriate C/N ratio, and sufficient microorganisms required for AD. The final cumulative methane yields from the co-digestion of CM:CP of ratios 80:20 and 20:80 were 739.97 mL and 838.70 mL, respectively, with average cumulative methane yields of 652.2 mL/day and 431.0 mL/day, respectively. The order of methane yield is 80:20 > 100:0 > 0:100 > 20:80, which could be attributed to the good digestibility of the CM and better interactions between the different substrates and the CM.

TABLE V
MATHEMATICAL ULTIMATE METHANE YIELD OF DIFFERENT CO-DIGESTION MIXTURES 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	$C_{70}H_{95}O_{42}N$	0.97	0.50
CM	6.62	1.14	53.95	6.39	36.82	55.21	78.47	28.26	1	$C_{55}H_{79}O_{28}N$	1.03	0.56
CM:CP (80:20)	6.54	1.10	54.24	6.37	38.28	57.48	81.60	30.43	1	$C_{58}H_{82}O_{30}N$	1.01	0.54
CM:CP (20:80)	7.30	0.92	52.31	6.00	40.77	66.00	90.81	38.58	1	$C_{66}H_{91}O_{39}N$	0.98	0.51

The results presented in Table V show an interesting trend. The ultimate methane yield obtained from mono-digestion with CM, followed by co-digestion of CM:CP at a ratio of 80:20, were 0.56 m^3/kg VS and 0.54 m^3/kg VS respectively. The lowest methane yield was obtained from mono-digestion with CP (0.50 m^3/kg VS).

IV. CONCLUSION

Co-digestion remains a suitable and simple method to improve the biogas production efficiency of mono-feedstock substrate. At similar ratios, co-digestion of feedstock substrate at different ratios is more suitable for maximum biogas production. Co-digestion helps to balance the nutrient ratio essential for microorganisms. The chemical composition of cassava showed a high biogas production potential due to high carbohydrate, dry matter (TS), and VS content, and low fibre content.

The highest methane production was achieved from the CM:CP co-digestion ratio of 20:80, whereas the mono-digestion of CP resulted in the lowest daily and cumulative methane yields. The study showed that increasing the CP ratio increased the cumulative biogas yield. This result could also introduce the possibility of using energy crops such as cassava as a capping measure for landfills, which could assist in utilisation of the landfill site after closure. Cassava peel could also be used for biogas generation at harvest. The results obtained from this study could be used as basis to design a plot sized anaerobic digester, and in turn large scale anaerobic digesters, thereby providing a source of renewable energy for low income communities.

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He has published a book titled "Biogas Production in Africa: Benefit Potentials of Cassava Biomass" by Saarbrücken: LAP Publishing GmbH in 2015 and also contributed to a technical report "The State of Waste to Energy Research in South Africa: A Review" published by SA DoE Renewable Energy Centre for Research and Development (RECORD).