



Nutrient Characterisation and Bioenergy Potential of Common Nigerian Food Wastes

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Abstract:	<p>Nigeria is the world's largest producer of yam, cassava, cocoyam/taro, beans/cowpea, egusi/melon seeds and among the largest producers of groundnut/peanut, plantain, corn/maize and uguwu/pumpkin leaves. These food crops generate unavoidable food wastes that can contribute to environmental degradation through unsanctioned waste disposal methods. Such food wastes can be utilised as feedstock for the Anaerobic Digestion process to produce renewable energy. In order to determine the suitability of the food wastes as biofuel feedstock, they were experimentally analysed. Their waste content were determined, characterised and used to evaluate their bio-methane potential. The tests were performed using standard proximate analytical methods while the bioenergy potential of the samples were determined using the Baserga Model. Results indicated a Specific Waste Index (SWI) range of 0.2 – 1.5, with corn having the highest waste proportion. The proximate analysis results of the wastes were within the range of common Anaerobic Digestion feedstocks such as energy crops and plant by products. The bio-methane potentials of the samples varied widely with results ranging from 35 – 460 m³ tonne⁻¹ on Fresh Weight and (5.4 – 6.2) × 10⁵ m³ kg⁻¹ on Volatile Solid basis. The methane potential varied between 51 – 58% of produced biogas. The energy potential of the food wastes was 31 TWh yr⁻¹ which can make a substantial contribution to the bioenergy production of the country and meet up to the energy demand of 4.7 × 10⁷ Nigerian households. Further studies would be required to determine the actual biogas yields of the food wastes.</p>

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Abstract

Nigeria is the world's largest producer of yam, cassava, cocoyam/taro, beans/cowpea, egusi/melon seeds and among the largest producers of groundnut/peanut, plantain, corn/maize and ugwu/pumpkin leaves. These food crops generate unavoidable food wastes that can contribute to environmental degradation through unsanctioned waste disposal methods. Such food wastes can be utilised as feedstock for the Anaerobic Digestion process to produce renewable energy. In order to determine the suitability of the food wastes as biofuel feedstock, they were experimentally analysed. Their waste content were determined, characterised and used to evaluate their bio-methane potential. The tests were performed using standard proximate analytical methods while the bioenergy potential of the samples were determined using the Baserga Model. Results indicated a Specific Waste Index (SWI) range of 0.2 – 1.5, with corn having the highest waste proportion. The proximate analysis results of the wastes were within the range of common Anaerobic Digestion feedstocks such as energy crops and plant by products. The bio-methane potentials of the samples varied widely with results ranging from 35 – 460 m³ tonne⁻¹ on Fresh Weight and (5.4 – 6.2) x 10⁵ m³ kg⁻¹ on Volatile Solid basis. The methane potential varied between 51 – 58% of produced biogas. The energy potential of the food wastes was 31 TWh yr⁻¹ which can make a substantial contribution to

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10 4.7×10^7 Nigerian households. Further studies would be required to determine
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12 the actual biogas yields of the food wastes.
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17 **Keywords**

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19 Anaerobic Digestion, Bio-Methane Potential, Specific Waste Index, Baserga
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Introduction

Renewable technologies allow the current energy demand to be met without compromising the ability of future generations to meet their own energy needs. There has been extensive research in this field in developed countries while developing nations are yet to fully embrace these technologies. One of such renewable technologies is Anaerobic Digestion (AD). The process involves the microbial degradation of organic compounds in an oxygen free environment for biogas production. Prior to adopting this technology, a sufficient supply of organic matter has to be identified and tested for its suitability as AD feedstock. Surveys such as NBS (2012) have shown that 39% of Nigerian households dump their domestic refuse in unauthorised heaps, while another 38% dispose theirs within their compounds by burying or burning the waste. The remaining households either dump their waste in approved dumpsites or have their wastes collected. The organic fraction of the refuse consists of food wastes which end up being burned, buried or discarded in water bodies, thus contributing to environmental degradation. These wastes will have to be analysed to determine their potential as AD feedstock. Currently there has been limited research on the biogas potentials of organic food wastes common to Nigeria. This may be occasioned by the unavailability of AD analysis equipment in such regions (Pham et al., 2013).

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8 The first step in analysing the suitability of an organic waste product for use as
9 an AD feedstock is its nutrient characterisation. The vast varieties of possible
10 feedstock for biogas production demonstrate the need for detailed
11 characterisation of each potential feedstock (Drosg et al., 2013). Knowledge of
12 the distribution of nutrients in a feedstock is required to determine its suitability
13 as a prime biofuel (Steffan et al., 1998). The performance of feedstock in a
14 digester can also be predicted with knowledge of the feedstock constituents.
15 This information is obtained from the different digestion rates of various
16 nutrients in digesters (Al Seadi et al., 2013). The availability of such data on
17 feedstock can be used for a preliminary evaluation on the fitness of such
18 materials as bioenergy raw material.
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32 Nine potential AD feedstocks were selected from food crops that have high
33 production values in Nigeria. These crops are Yam (*Dioscorea rotundata* Poir.),
34 Cassava (*Manihot esculenta* Crantz), Cocoyam/Taro (*Colocasia esculenta* (L.)
35 Schott), Plantain (*Musa paradisiaca* L.), Corn/Maize (*Zea mays* L.), Egusi/Melon
36 Seed (*Citrullus colocynthis* (L.) Schrader), Beans/Cowpea (*Vigna unguiculata*
37 (L.) Walp), Groundnut/Peanut (*Arachis hypogaea* L.) and Ugwu/Fluted Pumpkin
38 Leaves (*Telfairia occidentalis* Hook). Among these crops, the FAOSTAT
39 database (FAOSTAT, 2015) indicates that Nigeria is the world's largest
40 producer of yam (4.0×10^7 tonnes yr⁻¹), cassava (5.3×10^7 tonnes yr⁻¹),
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8 cocoyam (3.5×10^6 tonnes yr^{-1}), egusi (5.1×10^5 tonnes yr^{-1}) and beans ($2.9 \times$
9 10^6 tonnes yr^{-1}). Nigeria is also the third largest producer of groundnut ($3.0 \times$
10 10^6 tonnes yr^{-1}). Nigeria is also the third largest producer of groundnut ($3.0 \times$
11 10^6 tonnes yr^{-1}) in addition to being a major producer of plantain (2.8×10^6
12 tonnes yr^{-1}) and corn (1.0×10^7 tonnes yr^{-1}). There was no production data on
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ugwu leaves possibly due to its localised consumption in Nigeria. These high quantities of crops will produce equally high volumes of food waste, which can serve as raw materials for biofuel production. These common food crops and their waste products are shown in Figure 1.

This study focuses on providing a preliminary analysis on the suitability of the wastes of these nine crops as AD feedstock. This shall be accomplished by determining the waste content of each of the nine samples and subsequently performing a nutrient characterisation of their waste products. The study further determines the theoretical bio-methane potential of each of the food wastes in addition to their renewable energy potential. The main benefit of this study is filling the gap in literature on the waste content and composition of crops common to Nigeria. Another equally important benefit is the identification of abundant supplies of locally available feedstock that can be utilised to generate bioenergy. Implementation of the findings would also help in mitigating the environmental degradation from indiscriminate dumping of domestic waste.

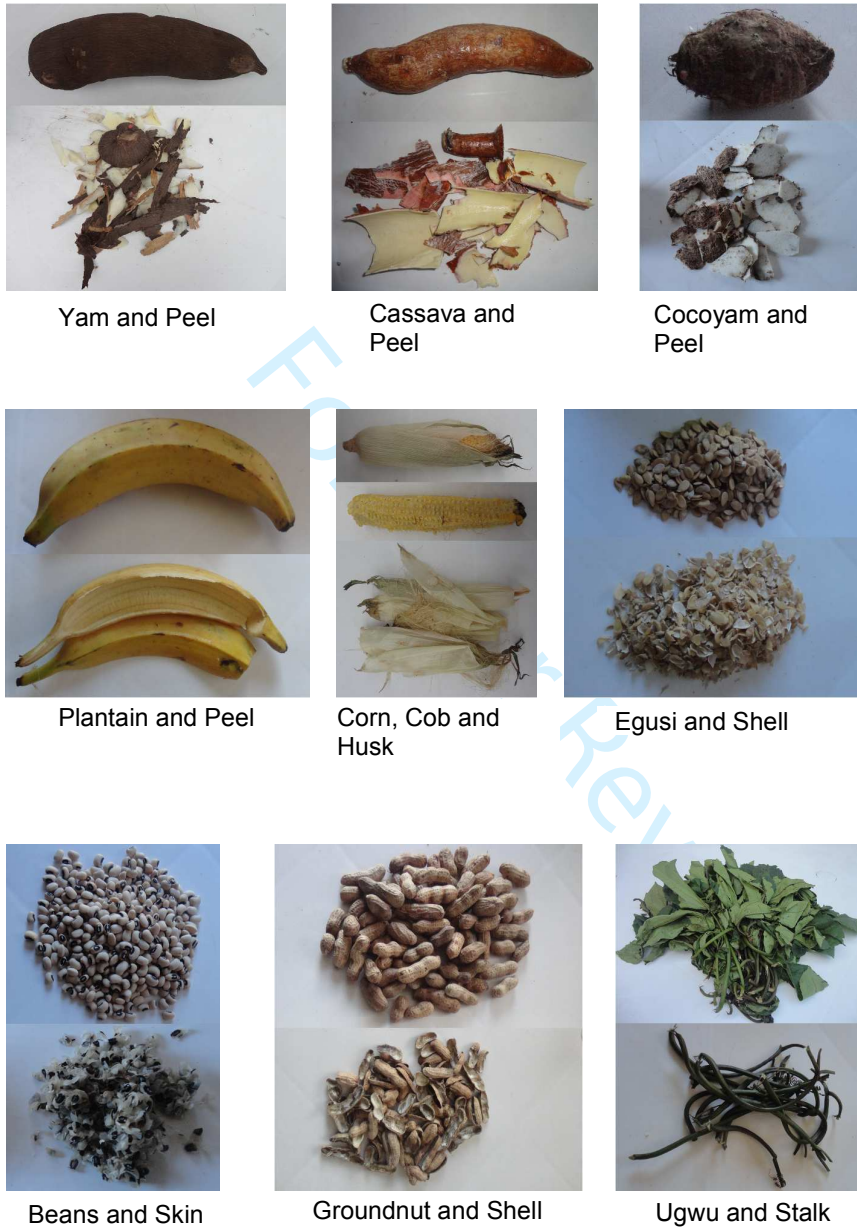


Figure 1. Pictures of nine common Nigerian food crops and their various waste products.

Materials and methods

Sample Collection

The nine crop samples were locally sourced from Nigeria and transported to Brunel University London, UK. The waste fractions were extracted from the samples using local Nigerian food processing methods. The wastes from the tubers which consist of yam, cassava and cocoyam are known as yam peel, cassava peel and cocoyam peel respectively. They were obtained by using a kitchen knife to cut off thin slices of their outer coats. The plantain's waste is known as plantain peel and was derived by using a knife to make a 5 mm insertion into the top of the plantain and then making a cut to the bottom. Fingers were then used to easily pull off its outer coat. Corn has two waste products, the husk and cob. The husk was peeled off the corn ear while the cob was obtained after the ear had been boiled and the kernels extracted. Egusi seeds produce a waste called egusi shell, which was collected by breaking off the outer coat of the seed with fingers. The waste from the beans is known as bean skin and was recovered after soaking the beans in water for four hours. That softened the skin which then easily came off when the beans were rubbed together using hands. Groundnut produces groundnut husk, which was extracted by cracking the nut with fingers. The waste of ugwu is the ugwu stalk, which was separated from the plant by stripping off the leaves.

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8 The substrates were decontaminated by rinsing with deionized water to remove
9 dust, coarse particles and other extraneous contaminants that could adversely
10 affect the test results. After rinsing, the substrates were dried in a fume hood to
11 remove surface moisture.
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18 ***Waste Content and Specific Waste Index***

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20 The weight of the foods and wastes were determined using an Adam
21 Equipment PGL 2002 Precision Balance. The results were used to determine
22 the waste content and Specific Waste Index (SWI) of the samples. The SWI is
23 the ratio of waste produced to the consumable product of a food sample (Russ
24 and Meyer-Pittroff, 2004). The equation for the SWI is shown in (Eq. 1). The
25 tests were performed in triplicates to improve accuracy.
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$$34 \text{ SWI} = \text{Mass}_{\text{accumulated waste}} / \text{Mass}_{\text{consumable Product}} \quad (1)$$

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38 ***Waste Nutrient Characterisation***

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40 The nutrient characteristics of the samples, including total solids, volatile solids,
41 crude fibre, crude protein, oils, Nitrogen Free Extracts, ash and moisture
42 content were determined using standard AOAC methods (AOAC, 2005). Due to
43 the requirement for analytical chemistry procedures, the food waste samples
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8 were sent to NRM laboratories, Bracknell, UK for the waste characterisation. A
9 brief description of the type of analyses that were performed is provided below.
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14 *Total Solids and Moisture Content*

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16 Total solid (TS) is the dry matter of a sample after all moisture has been
17 completely removed. To measure the TS, the sample was dried in an oven to a
18 constant weight at 105°C. The weight of the residue is the TS content of the
19 sample. The moisture content was obtained from subtracting the weight of the
20 TS from the initial weight of the sample.
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30 *Volatile Solids and Ash Content*

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32 Volatile Solids (VS) are the components of a sample that are lost on ignition at
33 550°C. To measure the VS, the sample is dried to constant weight in an oven at
34 105°C. After drying, the sample is weighted then placed in a furnace and
35 ignited at 550°C for four hours. The residue is then taken out of the furnace and
36 weighted. The residue is the Ash Content of the sample while the difference in
37 weight between the initial dry mass and the residue is the VS content.
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47 *Crude Fibre*

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8 Crude Fibre (CrF) is the complex carbohydrate of a sample. It consists of true
9 cellulose and insoluble lignin. Crude fibre is loss on ignition of dried residue
10 remaining after digestion of a sample with 1.25% H₂SO₄ and 1.25% NaOH
11 solutions. The sample was placed in a flask and the H₂SO₄ solution is added.
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13 The contents are then boiled for 30 minutes and then left to rest for one minute.
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15 The contents are then filtered and the residue is transferred to a flask with a
16 boiling NaOH solution for 30 minutes and left to rest for one minute. The residue
17 is then washed, dried and weighed.
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28 *Crude Protein*

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30 Crude Protein (CrP) is the amount of protein found in a sample as determined
31 by its Nitrogen content. It is analysed using Kjeldahl's method, which evaluates
32 the total nitrogen content of the sample after it has been digested in sulphuric
33 acid with a mercury or selenium catalyst.
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41 *Crude Fat*

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43 Crude fat (OAH) is the mixture of fat-soluble materials present in a sample. It
44 can also refer to the free lipid content. The analysis method involves the fats
45 being extracted from the sample with petroleum ether and evaluated as a
46 percentage of the weight before the solvent is evaporated.
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Nitrogen Free Extract (NFE)

Nitrogen Free Extracts are the non-Nitrogen soluble organic compounds including carbohydrates, such as starch and sugar. The value was calculated by subtracting the sum of the Crude Fibre, Crude Protein, Crude Oil and Ash from the Total Solids content.

Bio-Methane Potential

The theoretical Bio-Methane Potentials of the feedstock were determined using the Baserga Model (Baserga, 1998). The full sets of equations are shown in Appendix 1. The model is used to determine the theoretical bio-methane potential of a substrate based on its nutrient composition. The input data required for the use of the model are the Crude Fibre, Crude Protein, Crude Oils, Ash and Moisture content of the samples. The model assumes that all the organic content in the sample is converted to biogas.

Food Waste Quantification and Bioenergy Potential

The Nigerian production of each food crop was obtained from the FAOSTAT (2015) database. The data was then used in combination with the measured food waste content and their respective bio-methane potentials to determine the

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8 bioenergy potential of the crops. The equations used for the calculations are
9 presented in Appendix 2.
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14 **Statistical Analyses**

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17 The statistical analyses that were performed on the results are presented in this
18 section. The analyses were performed using computer programmes, specifically
19 IBM SPSS Statistics 23 and Microsoft Excel for Mac 2011.
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23 *Kruskal-Wallis Test*

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25 This test is a non-parametric alternative to the ANOVA test used when the
26 assumptions of the parametric tests are not met Such as when the variances
27 are not equal or the results do not form a normal distribution. The data from this
28 research fit into this category and were obtained from triplicate tests. The test
29 for normality was performed using the Chi-Square test.
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38 *Dunn's Test*

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40 This is a non-parametric post-hoc test that is used to determine the groups that
41 have significant differences between them. This is an appropriate complement
42 to the non-parametric Kruskal-Wallis Test.
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Results and Discussion

Specific Waste Index and Waste Content

The results of the Specific Waste Index (SWI) analysis of the crops showed an SWI range of 0.2 – 1.5 for the nine samples with an average value of 0.5. The results indicated that corn had the highest SWI range of 1.4 - 1.5 while cassava and egusi had the lowest values at 0.2 each. The results are presented in Table 1. The Total Waste Content (TWC) and the Organic Waste Content (OWC) of each crop are displayed in Figure 2. The TWC indicates the proportion of the crop that is non-consumable. The OWC indicates the organic fraction of the non-consumable part of the crop in proportion to the whole crop. The average TWC of the nine samples is 29% while the average OWC of the foods is 9%. Corn had the highest TWC of 59% from the husk and cob. The corn TWC has a low organic content of 30%. Uguwu had the second highest TWC of 37% with the lowest OWC of 2%. The lowest TWC is from egusi at 19% but the egusi shells have the highest organic content at 80%. Groundnut shell has the second highest organic content of its TWC at 78% while the groundnut has a low OWC of 19%.

Corn had the highest SWI value and was the only sample whose value was higher than 1.0. This indicated that it was the only crop that produced more

waste than consumable parts. Despite its high waste content, corn is ranked fourth when the organic content of its waste is considered.

Yam had high variations in waste content due to the large variation in tuber sizes, and different masses of edible materials that are unavoidably cut off with the peels. Plantain had the least variations as a result of uniform sizes of the plantains in addition to the peels being extracted without any of the edible parts. Beans and groundnuts also had low variations in waste content. Similar to plantain, their waste extraction processes do not take off any edible part of the crop, so the waste's proportions are uniform.

Table 1. Specific Waste Index of nine common Nigerian food crops.

Food	Food Waste	Specific Waste Index
Yam	Yam Peels*	0.3 - 0.5
Cassava	Cassava Peels*	0.2 - 0.3
Cocoyam	Cocoyam Peels*	0.3
Plantain	Plantain Peels*	0.5
Corn	Corn cob and husk	1.4 - 1.5
Egusi	Egusi shells	0.2 - 0.3
Beans	Beans skin	0.3
Groundnut	Groundnut shell	0.3
Ugwu	Ugwu stalk	0.5 - 0.6

* = Results from Longjan and Dehouche (2017)

Results from Russ and Meyer-Pittroff (2004) showed that oats, which are physically similar to egusi seeds, have an SWI of 0.4, which is higher than the value of 0.2 for egusi. Egusi has the least amount of TWC with a value of 19%.

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8 The seed has a low moisture content leading to dry and lightweight shells. The
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10 TWC of beans was 23% and consisted of moisture from its processing method.
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12 The results show that crops like corn, plantain and uguwu can have high TWC
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14 but the wastes will consist of low organic fractions. However crops like egusi
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16 and groundnut have low TWC, but high organic proportions.
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19 The results of Russ and Meyer-Pittroff (2004) showed that the only food whose
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21 SWI was greater than 1.0 was cheese, whose values got up to 11 for whey
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23 waste as a result of its processing method. None of the samples of this study
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25 obtained an SWI value as high as 2.0. Foods with high SWI are ideal for
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27 feedstock that will be considered in the anaerobic digestion chain. If SWI is the
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29 only factor, corn produces the best results. However if the organic content of the
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31 food waste has to be considered, then egusi is the ideal choice. The implication
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33 is that both factors have to be considered when selecting an appropriate food
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35 for its waste.
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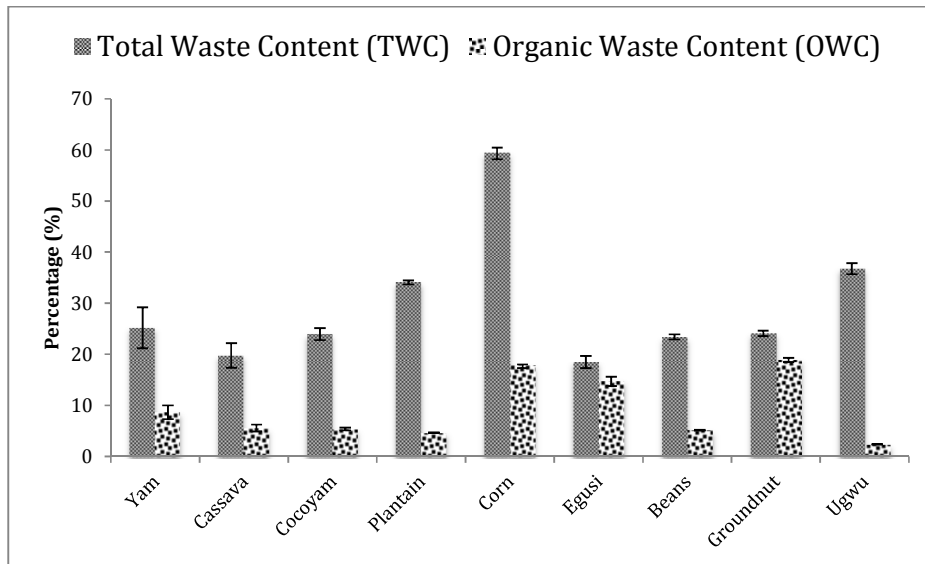


Figure 2. Waste content of nine Nigerian food crops showing the Total Waste Content (TWC) and Organic Waste Content (OWC). (Error bars indicating relative error of measurement).

A non-parametric Kruskal-Wallis test was performed on the waste analysis to determine if there was any significant difference between the waste content of the different crops. The results of the Kruskal-Wallis test indicated a significant difference between the samples ($p < 0.05$). The test did not show which samples were significantly different from each other. Hence a non-parametric post-hoc Dunn's test was performed to identify those significantly different groups. The results showed that there was significant different between various samples.

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8 Plantain was significantly different from Cassava. Corn was significantly
9 different from Yam, Cassava and Cocoyam. Egusi was significantly different
10 from Plantain and Corn. Beans was significantly different from Corn. While
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15 Ugwu was significantly different from Cassava and Egusi.
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18 19 ***Characterisation of food waste***

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21 The results of the characterisation of the food wastes are presented in Table 2.
22
23 The results from the TS analysis showed a high variation in TS content across
24 the samples. All samples, with the exception of ugwu stalk, were within the TS
25 range of plant waste and by-products as reported by Al Seadi et al (2013).
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Egusi shell and groundnut husk had the highest TS values which fell within the
70 - 90% values for straw. The TS for groundnut husk was lower than the 95%
obtained by Osman et al. (2006) but higher than the 71% obtained by Jekayinfa
and Omisakin (2005). The low amount of moisture in egusi shells and
groundnut husk is caused by the drying process the crops undergo prior to
being sold at the market. Ugwu stalk had the lowest TS at 8%. Feedstocks
having high TS content like egusi shell and groundnut husk require additional
water when digested. They also change the fluid dynamics of digesters leading
to process failure. This is caused by bad mixing behaviour, solids
sedimentation, clogging and scum layer formation (Steffan et al., 1998).

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8 Feedstocks with low TS values like uguwu stalk increase digester volume with a
9 low nutrient concentration. They also raise the heat input per m³ of feedstock
10 required, resulting in unfavourable process economics (Steffan et al., 1998).
11 The VS/TS analysis resulted in a narrow range of values, ranging from 87 -
12 97%. The results were within the range of VS/TS for plant wastes as reported
13 by Al Seadi et al (2013) and higher than the 70-80% for energy crops as
14 reported by Neureiter (2013). Common biodegradable organic matter should
15 have a VS/TS of at least 70% while feedstocks with lower than 60% VS/TS are
16 not suitable as feedstock for the AD process (Steffen et al., 1998). Uguwu stalk
17 had the lowest VS/TS contents at 87% but was still within the acceptable values
18 for AD feedstock. The VS content of a feedstock can be useful in bioenergy
19 estimations but it does not give information on the digestibility of the sample
20 (Drosg et al., 2013).
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36 The yam peel TS content was higher than the values obtained by (Ojikutu and
37 Osokoya, 2014; Makinde and Odokuma, 2015; Heiske et al, 2015) which
38 ranged from 19% to 23% TS. For cassava peel, the TS of 29% and VS/TS of
39 96% were within the ranges of 25 - 35% TS and 90 - 97% VS/TS reported by
40 (Cuzin et al., 1992; Jekayinfa and Scholz, 2013). For the cocoyam peel, the
41 24% TS and 91% VS/TS was close to the 27% TS and 92% VS/TS obtained by
42 Adeyosoye et al. (2010) while for plantain peel, the low values for TS of 15%
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was within the range of 13 – 15% obtained by (Ojikutu and Osokoya, 2014; Makinde and Odokuma, 2015). The differences in results is possibly due to non-standard testing methods used by the researchers.

Table 2. Characterisation of nine common Nigerian food wastes showing the results of their proximate analysis.

Food Waste	Yam Peels*	Cassava Peels*	Coco yam Peels*	Plantain Peels*	Corn cob & husk	Egusi shell	Bean skin	Ground nut Husk	Ugwu Stalk
Total Solids (%FW)	36.6	29.3	24.5	15.4	30.7	81.9	22.8	81.3	7.5
Volatile Solids (%FW)	34.3	28.0	22.4	13.6	29.8	79.5	22.0	78.4	6.5
Volatile Solids (%TS)	93.7	95.6	91.4	88.3	97.1	97.1	96.5	96.4	86.7
Crude Protein (%FW)	3.3	2.4	2.4	1.0	3.0	4.5	3.7	5.3	2.4
Crude Fibre (%FW)	2.4	2.3	2.7	1.2	6.5	64.9	6.2	62.3	1.9
Oil-B (%FW)	0.4	6.9	0.4	0.6	3.5	1.0	0.3	0.3	0.3
NFE (%FW)	28.2	16.4	16.9	10.8	16.8	9.1	11.8	10.5	1.9
Ash (%FW)	2.3	1.3	2.1	1.8	0.9	2.4	0.8	2.9	1.0
Moisture (%FW)	63.4	70.7	75.5	84.6	69.3	18.1	77.2	18.7	92.5

* = Values from (Longjan and Dehouche, 2017)

FW = Fresh Weight

TS = Total Solids

NFE = Nitrogen Free Extracts

The samples with the lowest moisture content had the highest amount of crude fibre and proteins. Groundnut husk and egusi shell had 5% FW protein content each. Groundnut husk's protein content was in line with the 5% FW obtained by Jekayinfa and Omisakin (2005). High amounts of protein in a feedstock can lead to high ammonia concentrations in the digester. The lowest fibre contents were for uguwu stalk and plantain peel each below 2% FW. Jekayinfa and

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8 Omisakin (2005) also obtained very low values of crude fibre for yam peels at
9 3% FW. High fibre feedstock can cause foaming and lignin incrustation in
10 digesters. Cassava peel, with a large margin, had the highest oil content at 7%
11 FW. This is due to cassava being covered in wax to prevent the tuber from
12 decomposing (Booth, 1973; Knoth, 1993; Onyenwoke and Simonyan, 2014).
13 Feedstock with high oil content leads to poor bioavailability and longer retention
14 times (Steffen et al., 1998). Excess oils in feedstock can have a detrimental
15 effect during digestion due to oils poor water solubility and ability to increase
16 VFA levels leading to low digester pH. The yam peels had the highest NFE
17 content while the lowest was the uguwu stalk. Groundnut husk had the highest
18 ash content of 3% FW.
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34 ***Theoretical Biogas Potential***

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36 The Bio-Methane Potential analysis, performed using the Baserga Model
37 equations detailed in Appendix 1, showed a narrow range of $(5.4 - 6.2) \times 10^5$
38 $\text{m}^3 \text{kg}^{-1} \text{VS}$ for biogas yields. The potential methane content varied between 51
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8 was a high variation in potential yield, ranging from 0.04 – 0.50 m³ kg⁻¹ FW with
9 an average potential of 0.2 m³ kg⁻¹ FW. The highest potential yields were from
10 the egusi shell and groundnut husk at 0.5 m³ kg⁻¹ FW each. They also had the
11 lowest methane potential of 51% each. The lowest biogas potential in this
12 category was from the uguwu stalk with a value of 0.04 m³ kg⁻¹ FW but had the
13 highest methane potential of 58%. The theoretical biogas yields on the volatile
14 solid and fresh weight basis are presented in Figure 3. Cassava peel had the
15 highest biogas potential on VS basis and second highest methane potential. On
16 a fresh weight basis it has the fifth highest potential. Its high moisture content at
17 71% leads to a low nutrient concentration in the digester leading to lower
18 energy output. The low moisture contents of egusi shell and groundnut husk at
19 18 and 19% respectively, allow them to have the highest fresh weigh yields.
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34 The range of results for biogas potentials on a volatile solid basis corresponds
35 to a wide variety of feedstock found in literature. Feedstock with similar yields
36 include vegetable waste, potato waste, food waste, fruit waste, slaughterhouse
37 waste and household waste as reported by (Deublein and Steinhauser, 2011).
38 This signifies that the biogas potentials of these common Nigerian food wastes
39 are within the range of values from conventional feedstock. This makes them
40 suitable candidates for anaerobic digestion feedstock. Nonetheless actual
41 biogas yields will be lower than their theoretical values due to the presence of
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8 non-degradable material and the consumption of 3-10% of the substrates by the
9 microbes for growth (VDI 4630, 2006). The nine food wastes fall into the
10 category of plant based feedstock with Drosig et al (2013) reporting that the
11 actual yields of such plant-based feedstock are 50-70% of their theoretical
12 values. Longjan and Dehouche (2017) showed that the bioenergy yields of
13 some common Nigerian food wastes ranged from 69 to 76% of their theoretical
14 values.
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23 Comparing the study's results with fresh weight biogas yields reported by
24 Korres et al (2013), egusi shell and groundnut husk had higher potentials than
25 barley, rye, sugar beet and rice straw which ranged from 0.2 – 0.3 m³ kg⁻¹. The
26 tubers in this study were the closest group to this lower range of yields. Egusi
27 shell and groundnut husk had yields that were within the range of 0.4 – 0.5 m³
28 kg⁻¹ of paper co-digested with chicken manure.
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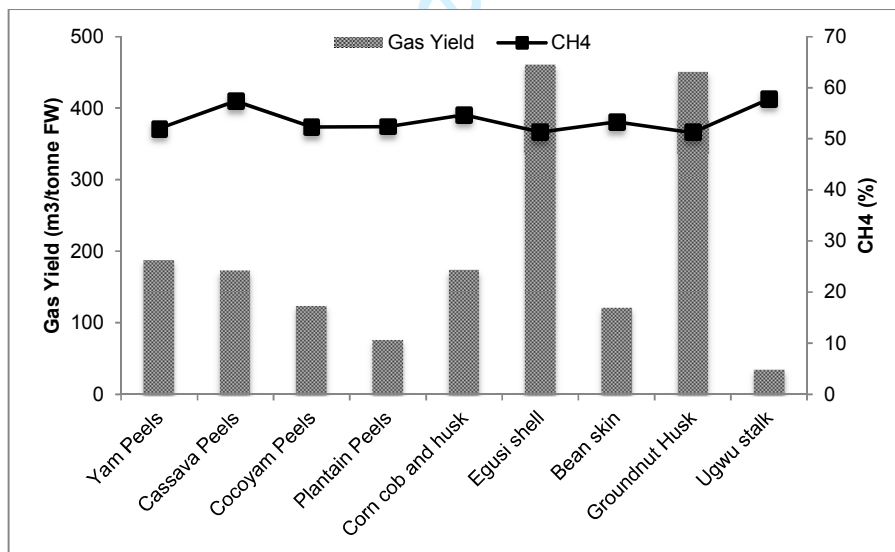
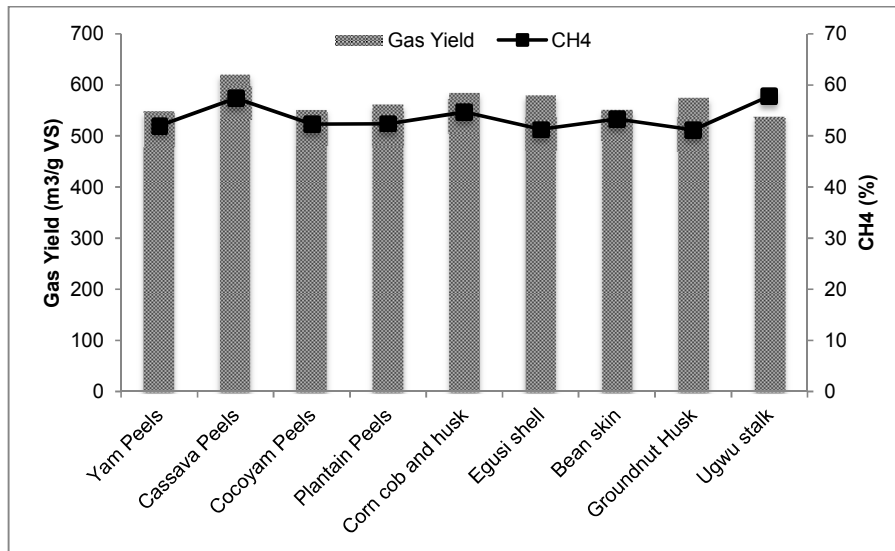


Figure 3. Bio-methane Potential of nine Nigerian food wastes on a Volatile Solid (VS) and Fresh Weight (FW) basis.

Regional Waste and Energy Potential

The waste quantification results were presented for eight out of the nine food crops because production data could not be obtained for ugwu leaves. Cassava had the highest waste potential at 1.0×10^7 tonnes yr^{-1} while egusi had the lowest potential of 9.4×10^4 tonnes yr^{-1} . The regional waste potential from the eight crops is 3.0×10^7 tonnes yr^{-1} . The annual waste potentials from the common Nigerian crops are presented in Table 3.

The projected methane yield from food waste in Nigeria is $30 \times 10^8 \text{ m}^3 \text{ yr}^{-1}$. The total renewable energy to be derived from that methane would be 31 TWh yr^{-1} . The bioenergy potentials of each food sample were calculated and are presented in Table 3. An analysis of the energy contribution of each food waste to bioenergy production shows that cassava contributes the most to the energy production at 35% while the least contribution is from egusi at less than 1%. The contribution of each waste is presented in Figure 4.

The projected maximum electricity demand of Nigeria for 2020 at 7% growth is 398.5 TWh yr^{-1} (REMP, 2012). The potential clean energy from the food waste in this study is 31 TWh yr^{-1} , which would meet 7.8% of the 2020 projected power demand.

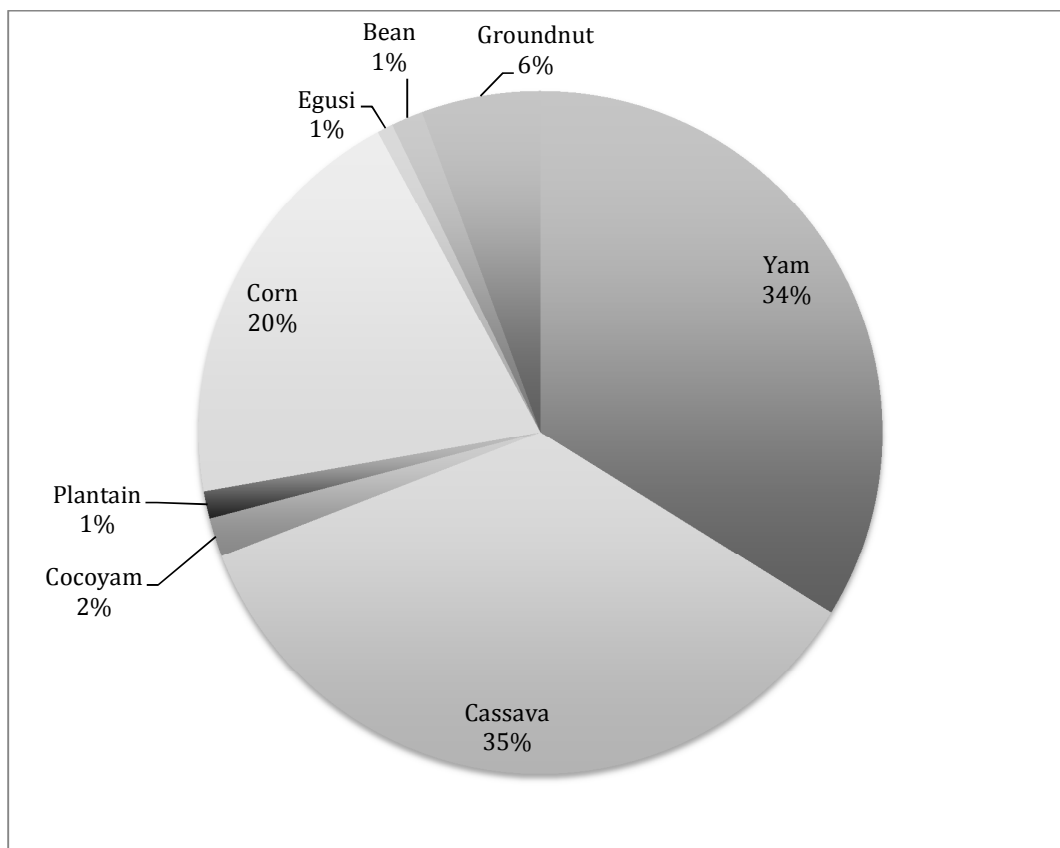
Table 3. Waste and Renewable Energy Potential of common Nigerian food crops.

Food	Production ¹ (10 ⁶ tonnes)	Food Waste (10 ⁶ tonnes)	Methane Potential (10 ⁸ m ³)	Energy Potential (10 ⁹ kWh)
Yam	40.5	10.2	10.0	10.6
Cassava	53.0	10.5	10.4	11.0
Cocoyam	3.5	0.8	0.5	0.6
Plantain	2.8	0.9	0.4	0.4
Corn	10.4	6.2	5.9	6.2
Egusi	0.5	0.1	0.2	0.2
Bean	2.9	0.7	0.4	0.5
Groundnut	3.0	0.7	1.7	1.8
Total	-	30.2	29.6	31.2

¹ Source: (FAOSTAT, 2015)

When considering the long-term projections (2021-2030) for electricity from biomass of 0.9 TWh yr⁻¹ (REMP, 2012), that projection would be surpassed by 3,367%. Considering more recent statistics, the potential bioenergy of this study is 1.1 times the total generated electrical energy in Nigeria for 2014, which was 29.7 TWh (GOPA, 2015). Based on Nigeria's electricity consumption per household of 655 kWh yr⁻¹ (WEC, 2016), the bioenergy of this study would meet up to the demand of 4.7×10^7 households. Using the Nigerian per capita electricity consumption of 142 kWh yr⁻¹ (World Bank, 2016), the food waste would provide energy that would meet the consumption of 2.2×10^8 individuals. The estimated energy from AD in this study is far higher than the total electricity from AD in the UK in 2014, which was 1.9 TWh (DEFRA, 2016) and also higher than the energy from biodegradable waste in the UK which was 1.9 TWh. Germany a leader in the renewable energy sector, attained 56.6 TWh of

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8 electricity from Bioenergy (Burger, 2016) which was far higher than that of the
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10 UK at 29.01 TWh (DECC, 2016). The potential Nigerian food waste is higher
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12 than that of the UK, where food and drink waste from households were 7 million
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14 tonnes (DEFRA, 2016).
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Figure 4. Potential Renewable Energy contributions of common Nigerian food wastes.

Conclusion

Nigeria is a leading producer of a wide range of food crops. Nine of these crops were analysed for their waste potential. They showed a wide range of Specific Waste Indexes of 0.2 – 1.5. Their food wastes were characterized and their nutrient profiles showed large variations in crude fibres, proteins, oils and nitrogen free extracts. Their theoretical bio-methane potential varied widely with results ranging from 35 - 460 m³ tonne⁻¹ on a Fresh Weight basis and (5.4 – 6.2) x 10⁵ m³ kg⁻¹ on a Volatile Solid basis. The values were within the acceptable range of currently utilised AD feedstock. The combined wastes have a renewable energy potential of 31 TWh yr⁻¹ which could meet up to the energy demand of 4.7 × 10⁷ Nigerian households. The results indicate that common Nigerian food crops produce wastes that are suitable as feedstock in the anaerobic digestion process. These wastes have the potential to significantly complement the energy production of the country. Further research will be required to determine the actual biogas yields of these feedstocks.

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Appendix 1: Baserga Model Equations

Digestibility factors:

<i>Crude Fibre</i>	(C_rFd)	74.3%
<i>Crude Protein</i>	(C_rPd)	65.09%
<i>Crude Fat</i>	$(OAHd)$	67.51%
<i>NFE</i>	(NFE_d)	69.97%

Gas Yield Conversion Factors:

<i>Carbohydrates</i>	$(GYCf)$	7901 kg^{-1}
<i>Proteins</i>	$(GYPf)$	7001 kg^{-1}
<i>Fat</i>	$(GYOf)$	12501 kg^{-1}

Methane content of Biogas:

<i>Carbohydrates</i>	(MCF)	50%
<i>Proteins</i>	(MPf)	71%
<i>Fats</i>	(Mof)	68%

Calculated Parameters

$$NFE = 100 - (C_rP + C_rF + OAH + Ash + Moisture)$$

$$VS = (C_rF + C_rP + OAH + NFE)$$

Baserga Equations:

$$\text{Digestible Carbohydrate } \left(\frac{g}{kg} \text{ DMB} \right) DC = ((C_rF \times C_rFd) + (NFE \times NFE_d))/10$$

$$\text{Digestible Crude Protein } \left(\frac{g}{kg} \text{ DMB} \right) DP = (C_rP \times C_rPd)/10$$

$$\text{Digestible Crude Fat } \left(\frac{g}{kg} \text{ DMB} \right) DO = (OAH \times OAHd)/10$$

And :

$$\text{Digestible Carbohydrate } \left(\frac{kg}{kg} VS \right) DCv = DC/(VS \times 10)$$

$$\text{Digestible Crude Protein } \left(\frac{kg}{kg} VS \right) DPv = DP/(VS \times 10)$$

$$\text{Digestible Crude Fat } \left(\frac{kg}{kg} VS \right) DOv = DO/(VS \times 10)$$

And :

$$\text{Gas Yield Carbohydrate } \left(\frac{l}{kg} VS \right) GYC = DCv \times GYCf$$

$$\text{Gas Yield Proteins } \left(\frac{l}{kg} VS \right) GYP = DPv \times GYPf$$

$$\text{Gas Yield Fat } \left(\frac{l}{kg} VS \right) GYO = DOv \times GYOf$$

$$\text{Total Gas Yield } \left(\frac{l}{kg} VS \right) TGY = GYC + GYP + GYO$$

And :

$$\text{Methane Share for Carbohydrates } (\%) MC = GYC \times MCf/TGY$$

$$\text{Methane Share for Protein } (\%) MP = GYP \times MPf/TGY$$

$$\text{Methane Share for Fats } (\%) MO = GYO \times MOf/TGY$$

$$\text{Total Methane Content } (\%) TMC = MC + MP + MO$$

And :

$$\text{Gas Yield } \left(\frac{m^3}{tonne} \right) \text{ of Fresh Matter} = (TGY \times VS)/100$$

Appendix 2: Calculations for Waste Quantification and Renewable Energy Potential of Nigeria

The following calculations were used to obtain the Waste and Renewable Energy Potentials of common Nigerian food crops.

Calculations:

Annual Food Waste (Tonnes) = *Annual Food Production (Tonnes)* × *Waste Content of food (%)*

Annual Biogas Potential (m³) = *Annual Food Waste (tonnes)* × *BioMethane Potential of Food Waste (m³/tonne)*

Annual Methane Potential (m³) = *Annual Biogas Potential (m³)* × *Methane Content (%)*

Annual Energy Potential (MJ) = *Annual Methane Potential (m³)* × *Gross Calorific Value Methane (MJ/m³)*

Annual Elect. Energy Potential (kWh/yr) = *Annual Energy Potential (MJ)* × 0.2778 kWh/MJ

Constants

Gross Calorific Value Methane = 38 MJ/m³

1 MJ = 0.2778 kWh

Abstract

Nigeria is the [world's](#) largest producer of yam, cassava, cocoyam/[taro](#), beans/[cowpea](#), egusi/melon seeds and among the largest producers of groundnut/[peanut](#), plantain, corn/[maize](#) and ugwu/pumpkin leaves. These food ~~cropps~~ generate unavoidable food wastes that can contribute to environmental degradation through unsanctioned waste disposal methods. Such food wastes can be utilised as feedstock for the [Anaerobic D](#)igestion process to produce renewable energy. In order to determine the suitability of the food wastes as biofuel feedstock, they ~~wereare~~ experimentally analysed. Their waste content ~~wereare~~ determined, characterised and used to evaluate their bio-methane potential. The tests were performed using standard proximate analytical methods while the bioenergy potential of the samples were determined using [the Baserga Model](#). ~~an the Baserga Model~~[appropriate model](#). Results indicated a Specific Waste Index (SWI) range of 0.2 – 1.5, with corn having the highest waste proportion. The proximate analysis results of the wastes were within the range of common [Anaerobic DigestionAD](#) feedstocks such as energy crops and plant by products. The bio-methane potentials of the samples varied widely with results ranging from 35 – 460 m³ tonne⁻¹ on Fresh Weight and (5.4 – 6.2) x 10⁵ m³ kg⁻¹ on Volatile Solid basis. The methane potential varied between 51 – 58% of produced biogas. The energy potential of the food wastes ~~wasis~~ 31 TWh yr⁻¹

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11 | which can make a substantial contribution to the bioenergy ~~mix-production~~ of
12 the country and meet up to the energy demand of 4.7×10^7 Nigerian
13 households. Further studies would be required to determine the actual biogas
14 yields of the food wastes.
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20 **Keywords**

21 Anaerobic Digestion, Bio-Methane Potential, Specific Waste Index, Baserga
22 Model, Food Waste, Waste to Energy
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Introduction

Renewable technologies allow the current energy demand to be met without compromising the ability of future generations to meet their own energy needs.

There has been extensive research in this field in developed countries while developing nations are yet to fully embrace these technologies. One of such renewable technologies is Anaerobic Digestion (AD). The process involves the microbial degradation of organic compounds in an oxygen free environment for biogas production. Prior to adopting this technology, a sufficient supply of organic matter has to be identified and tested for its suitability as AD feedstock.

Surveys such as (NBS, (2012) have shown that 39% of Nigerian households dump their domestic refuse in unauthorised heaps, while another 38% dispose theirs within their compounds by burying or burning the waste. The remaining households either dump their waste in approved dumpsites or have their wastes collected. The organic fraction of the refuse consists of food wastes which end up being burned, buried or discarded in water bodies, thus contributing to environmental degradation. These wastes will have to be analysed to determine their potential as AD feedstock. Currently there has been limited research on the biogas potentials of organic food wastes local common to Nigeria. This may be occasioned by the unavailability of AD analysis equipment in such regions (Pham et al., 2013).

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11 The first step in analysing the suitability of an organic waste product for use as
12 an AD feedstock is its nutrient characterisation. The vast varieties of possible
13 feedstock for biogas production demonstrate the need for detailed
14 characterisation of each potential feedstock (Drosg et al., 2013). Knowledge of
15 the distribution of nutrients in a feedstock is required to determine its suitability
16 as a prime biofuel (Steffan et al., 1998). The performance of feedstock in a
17 digester can also be predicted with knowledge of the feedstock constituents.
18 This information is obtained from the different digestion rates of various
19 nutrients in digesters (Al Seadi et al., 2013). The availability of such data on
20 feedstock can be used for a preliminary evaluation on the fitness of such
21 materials as bioenergy raw material.
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32 Nine potential AD feedstocks were selected from food ~~crops~~ that have high
33 production values in Nigeria. The ~~food items-se crops~~ are Yam (*Dioscorea*
34 *rotundata* Poir.), Cassava (*Manihot esculenta* Crantz), Cocoyam/Taro
35 (*Colocasia esculenta* (L.) Schott), Plantain (*Musa paradisiaca* L.), Corn/Maize
36 (*Zea mays* L.), Egusi/Melon Seed (*Citrullus colocynthis* (L.) Schrader),
37 Beans/Cowpea (*Vigna unguiculata* (L.) Walp), Groundnut/Peanut (*Arachis*
38 *hypogaea* L.) and Ugwu/Fluted Pumpkin Leaves (*Telfairia occidentalis* Hook).

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45 Among these ~~cropsfood items~~, the FAOSTAT database (FAOSTAT, 2015)
46 indicates that Nigeria is the world's largest producer of yam (4.0×10^7 tonnes
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11 yr⁻¹), cassava (5.3×10^7 tonnes yr⁻¹), cocoyam (3.5×10^6 tonnes yr⁻¹), egusi (5.1
12 $\times 10^5$ tonnes yr⁻¹) and beans (2.9×10^6 tonnes yr⁻¹). Nigeria is also the third
13 largest producer of groundnut (3.0×10^6 tonnes yr⁻¹) in addition to being a major
14 producer of plantain (2.8×10^6 tonnes yr⁻¹) and corn (1.0×10^7 tonnes yr⁻¹).
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16 There was no production data on ugu leaves possibly due to its localised
17 consumption in Nigeria. These high quantities of feed-crops will produce equally
18 high volumes of food waste, which can serve as raw materials for biofuel
19 production. These common food crops and their waste products are shown in
20 Figure 1.
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28 This study focuses on providing a preliminary analysis on the suitability of the
29 wastes of these nine crops as AD feedstock. This shall be accomplished
30 by determining the waste content of each of the nine feed-samples and
31 subsequently performing a nutrient characterisation of their waste products. The
32 study further determines the theoretical bio-methane potential of each of the
33 food wastes in addition to their renewable energy potential. The main benefit of
34 this study is filling the gap in literature on the waste content and composition of
35 feed-crops common to Nigeria. Another equally important benefit is the
36 identification of abundant supplies of locally available feedstock that can be
37 utilised to generate bioenergy. Implementation of the findings would also help in
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11 mitigating the environmental degradation from indiscriminate dumping of
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13 domestic waste.
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For Peer Review

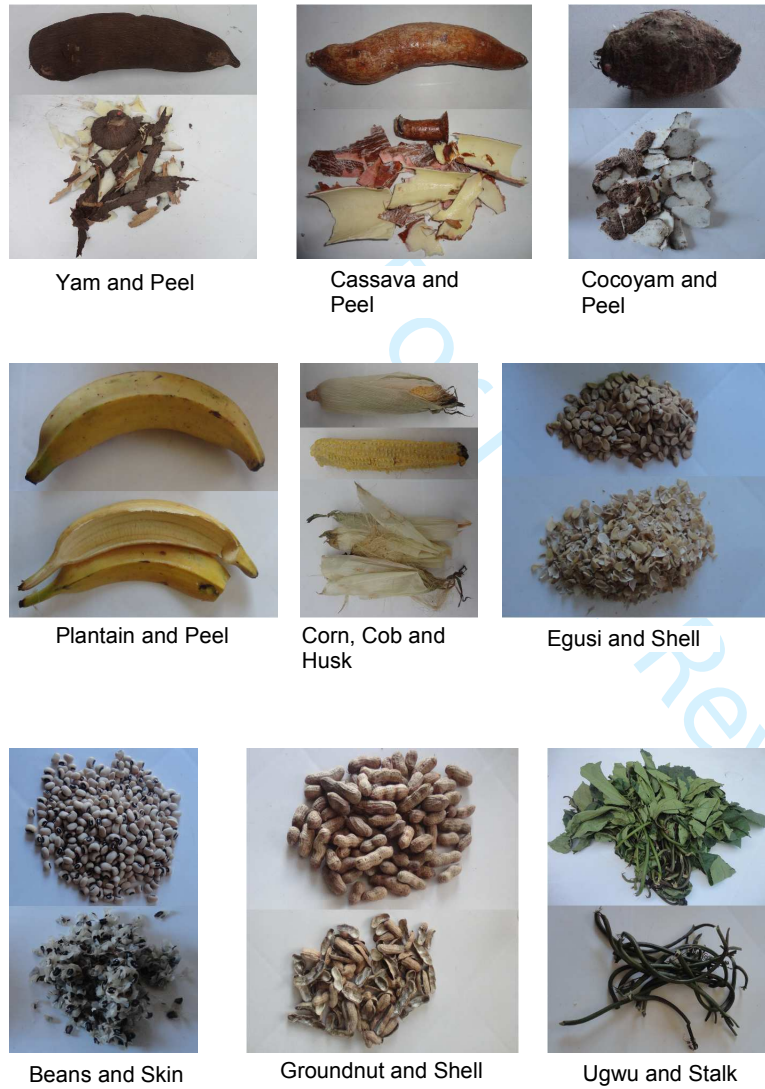


Figure 1. Pictures of nine common Nigerian food crops and their various waste products.

Materials and methods

Sample Collection

The nine ~~crop~~ ~~feed~~ samples were locally sourced from Nigeria and transported to Brunel University London, UK. The waste fractions were extracted from the ~~samples~~ ~~feeds~~ using local Nigerian food processing methods. The wastes from the tubers which consist of yam, cassava and cocoyam are known as yam peel, cassava peel and cocoyam peel respectively. They ~~were~~ ~~are~~ obtained by using a kitchen knife to cut off thin slices of their outer coats. The plantain's waste is known as plantain peel and wasis derived by using a knife to make a 5 mm insertion into the top of the plantain and then making a cut to the bottom. Fingers ~~were~~ ~~are~~ then used to easily pull off its outer coat. Corn has two waste products, the husk and cob. The husk wasis peeled off the corn ear while the cob wasis obtained after the ear had ~~s~~ been boiled and the kernels extracted. Egusi seeds produce a waste called egusi shell, which wasis collected by breaking off the outer coat of the seed with fingers. The waste from the beans is known as bean skin and wasis recovered after soaking the beans in water for four hours. ~~That~~ ~~is~~ ~~soften~~ ~~eds~~ the skin which then easily ~~comes~~ ~~came~~ off when the beans ~~were~~ ~~are~~ rubbed together using hands. Groundnut produces groundnut husk, ~~that~~ ~~which~~ wasis extracted by cracking the nut with fingers. The

waste of uguwu is the uguwu stalk, which [was](#) separated from the plant by stripping off the leaves.

The substrates were decontaminated by rinsing with deionized water to remove dust, coarse particles and other extraneous contaminants that could adversely affect the test results. After rinsing, the substrates were dried in a fume hood to remove surface moisture.

Waste Content of Food and Specific Waste Index

The weight of the foods and wastes were determined using an Adam Equipment PGL 2002 Precision Balance. The results were used to determine the waste content and Specific Waste Index (SWI) of the samples. The SWI is the ratio of waste produced to the consumable product of a food sample (Russ and Meyer-Pittroff, 2004). The equation for the SWI is shown in (Eq. 1). The tests were performed in triplicates to improve accuracy.

$$SWI = \frac{Mass_{accumulated\ waste}}{Mass_{consumable\ Product}} \quad (1)$$

Waste Nutrient Characterisation

The nutrient characteristics of the samples, including total solids, volatile solids, crude fibre, crude protein, oils, Nitrogen Free Extracts, ash and moisture content were determined using standard AOAC methods (AOAC, 2005). [Due to](#)

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11 the requirement for analytical chemistry procedures, the food waste samples
12 were sent to NRM laboratories, Bracknell, UK for the waste characterisation. A
13 brief description of the type of analyses that were performed is provided below.
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18 *Total Solids and Moisture Content*

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20 Total solid (TS) is the dry matter of a sample after all moisture has been
21 completely removed. To measure the ~~total solids~~TS, the sample ~~wasis~~ dried in
22 an oven to a constant weight at 105°C. The weight of the residue is then
23 weighed and compared to the initial sample weight. The result is the TS total
24 solid content of the sample. The moisture content ~~wasis~~ obtained from
25 subtracting the weight of the TS from the initial weight of the sample.
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33 *Volatile Solids and Ash Content*

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35 Volatile Solids (VS) are the ~~organic dry matter of a components of a~~ sample that
36 are lost on ignition at 550°C. To measure the VS, the sample is dried to
37 constant weight in an oven at 105°C. After drying, the sample is weighed then
38 placed in a furnace and ignited ~~in a furnace~~ at 550°C for four hours. The
39 residue is then taken out of the furnace and weighed. The residue is the Ash
40 Content of the sample while tThe difference in weight between the initial dry
41 mass and the residue is the ~~volatile solid~~VS content.
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Crude Fibre

Crude Fibres (CrF) isare the complex carbohydrates of a sample. It consists of true cellulose and insoluble lignin. Crude fibre is loss on ignition of dried residue remaining after digestion of a sample with 1.25% H₂SO₄ and 1.25% NaOH solutions. The sample wasis placed in a flask and the H₂SO₄ solution is added. The contents are then boiled for 30 minutes and then left to rest for one minute. The contents are then filtered and the residue is transferred to a flask with a boiling NaOH solution for 30 minutes and left to rest for one minute. The residue is then washed, dried and weighed.

Crude Protein

Crude Protein (CrP) is the amount of protein found in a sample as determined by its Nitrogen content. It is analysed using Kjeldahl's method, which evaluates the total nitrogen content of the sample after it has been digested in sulphuric acid with a mercury or selenium catalyst.

Crude Fat

Crude fat (OAH) is the mixture of fat-soluble materials present in athe sample. It can also refer to the free lipid content. The analysis method involves the fats

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11 being extracted from the sample with petroleum ether and evaluated as a
12 percentage of the weight before the solvent is evaporated.
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15 16 *Nitrogen Free Extract (NFE)*

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18 Nitrogen Free Extracts are the non-Nitrogen soluble organic compounds
19 including carbohydrates, such as starch and sugar. The value wasis calculated
20 by subtracting the sum of the Crude Fibre, Crude Protein, Crude Oil and Ash
21 from the Total Solids content.
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25 26 *Ash*

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28 ~~The Ash is the total mineral matter of a sample. To measure the value, a~~
29 ~~sample is dried to constant weight in an oven. After drying, the sample is~~
30 ~~weighed then placed in a furnace and ignited at 550°C for four hours. The~~
31 ~~residue is then taken out of the furnace and weighed and the result indicates~~
32 ~~the ash content of the sample.~~
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36 37 *Moisture Content*

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39 ~~The moisture content is the liquid component of a sample. To measure the~~
40 ~~moisture content, the sample is initially weighed. Next the sample is dried in an~~
41 ~~oven to a constant weight at 105°C. The residue is then weighed and its weight~~
42 ~~is subtracted from the initial weight of the sample. The final result, which~~
43 ~~indicates the loss in weight, is the moisture content of the sample.~~
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Bio-Methane Potential

The theoretical Bio-Methane Potentials of the feedstock were determined using the Baserga Model (Baserga, 1998). The full sets of equations are shown in Appendix 1. The model is used to determine the theoretical bio-methane potential of a substrate based on its nutrient composition. The input data required for the use of the model are the Crude Fibre, Crude Protein, Crude Oils, Ash and Moisture content of the samples. The model assumes that all the organic content in the sample is converted to biogas.

Food Waste Quantification and Bioenergy Potential

The Nigerian production of each food ~~item~~ crop was obtained from the FAOSTAT (2015) database. The data was then used in combination with the measured food waste content and their respective bio-methane potentials to determine the bioenergy potential of the ~~feedscrops~~. The equations used for the calculations are presented in Appendix 2.

Statistical Analyseis

The ~~various~~ statistical analyses that were performed on the results are presented in this section. The analyses were performed using computer

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11 programmes, specifically IBM SPSS [Statistics 23](#) and Microsoft Excel [for Mac](#)
12 [2011](#).

13 14 *Kruskal-Wallis Test*

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16 This test is a non-parametric alternative to the ANOVA test used when the
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18 assumptions of the parametric tests are not met. Such as when the variances
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20 are not equal or the results do not form a normal distribution. [The data from this](#)
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22 [research fit into this category and were obtained from triplicate tests. The test](#)
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24 [for normality was performed using the Chi-Square test.](#)

25 26 *Dunn's Test*

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28 This is a non-parametric post-hoc test that is used to determine the groups that
29
30 have significant differences between them. [This is an appropriate complement](#)
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32 [to the non-parametric Kruskal-Wallis Test.](#)

33 34 35 36 37 **Results and Discussion**

38 39 ***Specific Waste Index and Waste Content of food***

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41 The results of the Specific Waste Index (SWI) analysis of the ~~food~~
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43 ~~samples~~[crops](#) showed an SWI range of 0.2 – 1.5 for the nine ~~foods~~[samples](#)
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45 with an average value of 0.5. The results indicated that corn had the highest
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47 SWI range of 1.4 - 1.5 while cassava and egusi had the lowest values at 0.2
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11 each. The results are presented in Table 1. The Total Waste Content (TWC)
12 and the Organic Waste Content (OWC)s of each crop ~~food and their waste~~
13 ~~organic content (OWC/TWC)~~ are displayed in Figure 2. The TWC indicates the
14 proportion of the crop that is non-consumable. The OWC indicates the amount
15 ~~of waste in the food that is organic in composition~~ organic fraction of the non-
16 consumable part of the crop in proportion to the whole crop. The average ~~total~~
17 ~~waste content~~ TWC of the nine ~~food items~~ samples is 29% while the average
18 ~~organic waste content~~ OWC of the foods is 9%. Corn had the highest ~~waste~~
19 ~~content~~ TWC of 59% from the husk and cob. The corn ~~wastes~~ TWC has a low
20 organic content of 30%. Uguwu had the second highest ~~waste content~~ TWC of
21 37% with the lowest ~~organic waste content~~ OWC of 2%. The lowest ~~waste~~
22 ~~content~~ TWC is from egusi at 19% but the egusi shells have the highest organic
23 content at 80%. Groundnut shell has the second highest organic content of its
24 TWC at 78% while the groundnut has a low ~~organic waste content~~ OWC of 19%.

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Corn had the highest SWI value and was the only sample whose value was
higher than 1.0. This indicated that it was the only ~~food item~~ crop that, which
produced more waste than consumable parts. Despite its high waste content,
corn is ~~the fourth~~ ranked fourth when the organic content of its waste is
considered.

Yam had high variations in waste content due to the large variation in tuber sizes, and different masses of edible materials that are unavoidably cut off with the peels. Plantain had the least variations as a result of uniform sizes of the plantains in addition to the peels being extracted without any of the edible parts. Beans and groundnuts also had low variations in waste content. Similar to plantain, their waste extraction processes do not take off any edible part of the ~~food item~~crop, so the waste's proportions are uniform.

Table 1. Specific Waste Index of nine common Nigerian food ~~crop~~s.

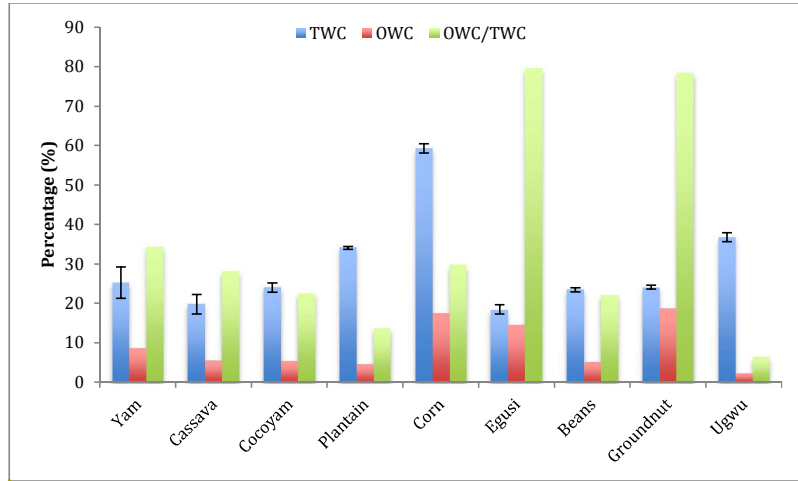
Food	Food Waste	Specific Waste Index
Yam	Yam Peels*	0.3 - 0.5
Cassava	Cassava Peels*	0.2 - 0.3
Cocoyam	Cocoyam Peels*	0.3
Plantain	Plantain Peels*	0.5
Corn	Corn cob and husk	1.4 - 1.5
Egusi	Egusi shells	0.2 - 0.3
Beans	Beans skin	0.3
Groundnut	Groundnut shell	0.3
Ugwu	Ugwu stalk	0.5 - 0.6

* = Results from (Longjan and Dehouche, (2017)

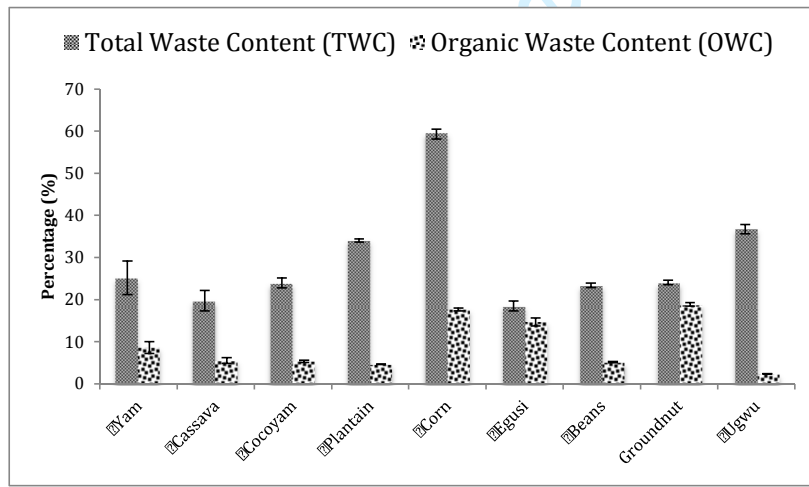
Results from (Russ and Meyer-Pittroff, (2004) showed that oats, which are physically similar to egusi seeds, have an SWI of 0.4, which is higher than the value of 0.2 for egusi. Egusi has the least amount of ~~total waste~~TWC with a value of 19%. The seed has a low moisture content leading to dry and lightweight shells. The ~~total waste content~~TWC of beans was 23% and

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11 consisted of moisture from its processing method. The results show that ~~foods~~
12 ~~crops~~ like corn, plantain and ugwu can have high ~~waste contents~~TWC but the
13 ~~wastes~~ will consist of low organic fractions. However ~~foods-crops~~ like egusi and
14 groundnut have low ~~waste contents~~TWC, but high organic proportions.

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18 The results of (Russ and Meyer-Pittroff, (2004) showed that the only food
19 whose SWI was greater than 1.0 was cheese, whose values got up to 11 for
20 whey waste as a result of its processing method. None of the samples of this
21 study obtained an SWI value as high as 2.0. Foods with high SWI are ideal for
22 feedstock that will be considered in the anaerobic digestion chain. If SWI is the
23 only factor, corn produces the best results. However if the organic content of the
24 food waste has to be considered, then egusi is the ideal choice. The implication
25 is that both factors have to be considered when selecting an appropriate food
26 for its waste.
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Figure 2. Waste content of nine Nigerian food cropps showing the Total Waste Content (TWC) and Organic Waste Content (OWC) -and the relationship

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11 ~~between OWC and TWC~~ (~~E-TWC~~ error bars indicating relative error of
12 measurement).

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16 ~~In the UK, unavoidable food waste such as the ones analysed in this study~~
17 ~~account for 19% of the total annual food waste in the country. 26% of all food~~
18 ~~waste comes from vegetables, while 82% of the vegetable wastes are either~~
19 ~~unavoidable or potentially avoidable waste (WRAP, 2008).~~

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24 A non-parametric Kruskal-Wallis test was performed on the [waste analysis](#)
25 [results](#) to determine if there was any significant difference between the [waste](#)
26 [content of the samples](#) [different foodscrops](#). The results of the Kruskal-Wallis
27 test indicated a significant difference between the samples ($p < 0.05$). The test
28 did not show which samples were significantly different from each other. Hence
29 a non-parametric post-hoc Dunn's test was performed to identify those
30 significantly different groups. The results showed that there was significant
31 difference between various samples. Plantain was significantly different from
32 Cassava. Corn was significantly different from Yam, Cassava and Cocoyam.
33 Egusi was significantly different from Plantain and Corn. Beans was significantly
34 different from Corn. While Ugwu was significantly different from Cassava and
35 Egusi. ~~The statistical analyses were performed using the SPSS IBM software~~
36 ~~package.~~

Characterisation of food waste

The results of the characterisation of the food wastes are presented in Table 2.

The results from the TS analysis showed a high variation in TS content across the samples. All samples, with the exception of ugwu stalk, were within the TS range of plant waste and by-products as reported by Al Seadi et al (2013).

Egusi shell and groundnut husk had the highest TS values which fell within the 70 - 90% values for straw. The TS for groundnut husk was lower than the 95%

obtained by Osman et al. (2006) but higher than the 71% obtained by Jekayinfa and Omisakin (2005). The low amount of moisture in egusi shells and

groundnut husk is caused by the drying process the ~~feeds-crops~~ undergo prior to being sold at the market. Ugwu stalk had the lowest TS at 8%. Feedstocks

having high TS content like egusi shell and groundnut husk require additional water when digested. They also change the fluid dynamics of digesters leading to process failure. This is caused by bad mixing behaviour, solids sedimentation, clogging and scum layer formation (Steffan et al., 1998).

Feedstocks with low TS values like ugwu stalk increase digester volume with a low nutrient concentration. They also raise the heat input per m³ of feedstock required, resulting in unfavourable process economics (Steffan et al., 1998).

The VS/TS analysis resulted in a narrow range of values, ranging from 87 -

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11 97%. The results were within the range of VS/TS for plant wastes as reported
12 by Al Seadi et al (2013) and higher than the 70-80% for energy crops as
13 reported by Neureiter (2013). Common biodegradable organic matter should
14 have a VS/TS of at least 70% while feedstocks with lower than 60% VS/TS are
15 not suitable as feedstock for the AD process (Steffen et al., 1998). Ugwu stalk
16 had the lowest VS/TS contents at 87% but was still within the acceptable values
17 for AD feedstock. The VS content of a feedstock can be useful in bioenergy
18 estimations but it does not give information on the digestibility of the sample
19 (Drosg et al., 2013).

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28 The yam peel TS content was higher than the values obtained by (Ojikutu and
29 Osokoya, 2014; Makinde and Odokuma, 2015; Heiske et al, 2015) which
30 ranged from 19% to 23% TS. For cassava peel, the TS of 29% and VS/TS of
31 96% were within the ranges of 25 - 35% TS and 90 - 97% VS/TS reported by
32 (Cuzin et al., 1992; Jekayinfa and Scholz, 2013). For the cocoyam peel, the
33 24% TS and 91% VS/TS was close to the 27% TS and 92% VS/TS obtained by
34 Adeyosoye et al. (2010) while for plantain peel, the low values for TS of 15%
35 was within the range of 13 – 15% obtained by (Ojikutu and Osokoya, 2014;
36 Makinde and Odokuma, 2015). The differences in results is possibly due to non-
37 standard testing methods used by the researchers.
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Table 2. Characterisation of nine common Nigerian food wastes showing the results of their proximate analysis.

Food Waste	Yam Peels*	Cassava Peels*	Coco yam Peels*	Plantain Peels*	Corn cob & husk	Egusi shell	Bean skin	Ground nut Husk	Ugwu Stalk
Total Solids (%FW)	36.6	29.3	24.5	15.4	30.7	81.9	22.8	81.3	7.5
Volatile Solids (%FW)	34.3	28.0	22.4	13.6	29.8	79.5	22.0	78.4	6.5
Volatile Solids/VS/TS (%TS)	93.7	95.6	91.4	88.3	97.1	97.1	96.5	96.4	86.7
Crude Protein (%FW)	3.3	2.4	2.4	1.0	3.0	4.5	3.7	5.3	2.4
Crude Fibre (%FW)	2.4	2.3	2.7	1.2	6.5	64.9	6.2	62.3	1.9
Oil-B (%FW)	0.4	6.9	0.4	0.6	3.5	1.0	0.3	0.3	0.3
NFE (%FW)	28.2	16.4	16.9	10.8	16.8	9.1	11.8	10.5	1.9
Ash (%FW)	2.3	1.3	2.1	1.8	0.9	2.4	0.8	2.9	1.0
Moisture (%FW)	63.4	70.7	75.5	84.6	69.3	18.1	77.2	18.7	92.5

* = Values from (Longjan and Dehouche, 2017)

~~NFE = Nitrogen Free Extracts~~ FW = Fresh Weight

~~TS = Total Solids~~

~~NFE = Nitrogen Free Extracts~~

~~* = Values from (Longjan and Dehouche, 2017)~~

The samples with the lowest moisture content had the highest amount of crude fibre and proteins. Groundnut husk and egusi shell had 5% FW protein content each. Groundnut husk's protein content was in line with the 5% FW obtained by Jekayinfa and Omisakin (2005). High amounts of protein in a feedstock can lead to high ammonia concentrations in the digester. The lowest fibre contents were for uguwu stalk and plantain peel each below 2% FW. Jekayinfa and Omisakin (2005) also obtained very low values of crude fibre for yam peels at

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11 3% [FW](#). High fibre feedstock can cause foaming and lignin incrustation in
12 digesters. Cassava peel, with a large margin, had the highest oil content at 7%
13 [FW](#). This is due to cassava being covered in wax to prevent the tuber from
14 decomposing (Booth, 1973; Knoth, 1993; Onyenwoke and Simonyan, 2014).
15
16 Feedstock with high oil content leads to poor bioavailability and longer retention
17 times (Steffen et al., 1998). Excess oils in feedstock can have a detrimental
18 effect during digestion due to oils poor water solubility and ability to increase
19 VFA levels leading to low digester pH. The yam peels had the highest NFE
20 content while the lowest was the uguwu stalk. Groundnut husk had the highest
21 ash content of 3% [FW](#).
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31 ***Theoretical Biogas Potential***

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33 The Bio-Methane Potential analysis, [performed using the Baserga Model](#)
34 [equations detailed in Appendix 1](#), showed a narrow range of $(5.4 - 6.2) \times 10^5$
35 $\text{m}^3 \text{kg}^{-1} \text{VS}$ for biogas yields. The potential methane content varied between 51
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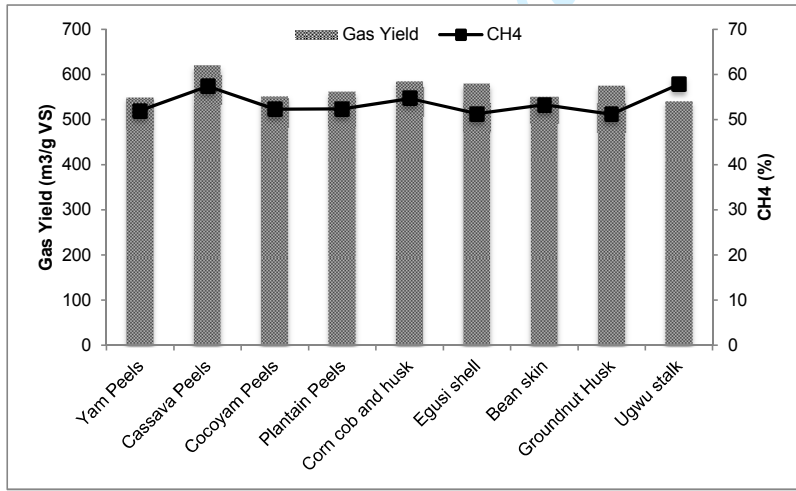
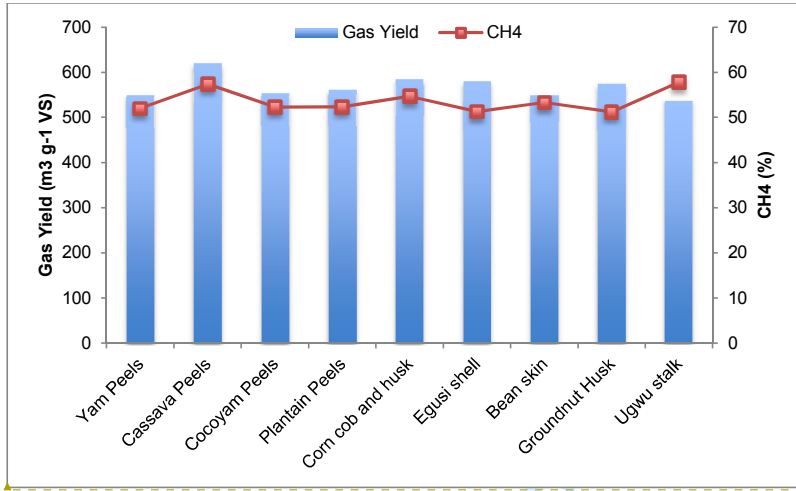
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11 an average potential of $0.2 \text{ m}^3 \text{ kg}^{-1}$ FW. The highest potential yields were from
12 the egusi shell and groundnut husk at $0.5 \text{ m}^3 \text{ kg}^{-1}$ FW each. They also had the
13 lowest methane potential of 51% each. The lowest biogas potential in this
14 category was from the uguwu stalk with a value of $0.04 \text{ m}^3 \text{ kg}^{-1}$ FW but had the
15 highest methane potential of 58%. The theoretical biogas yields on the volatile
16 solid and fresh weight basis are presented in Figure 3. Cassava peel had the
17 highest biogas potential on VS basis and second highest methane potential. On
18 a fresh weight basis it has the fifth highest potential. Its high moisture content at
19 71% leads to a low nutrient concentration in the digester leading to lower
20 energy output. The low moisture contents of egusi shell and groundnut husk at
21 18 and 19% respectively, allow them to have the highest fresh weigh yields.

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31 The range of results for biogas potentials on a volatile solid basis corresponds
32 to a wide variety of feedstock found in literature. Feedstock with similar yields
33 include vegetable waste, potato waste, food waste, fruit waste, slaughterhouse
34 waste and household waste as reported by (Deublein and Steinhauser, 2011).
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60 This signifies that the biogas potentials of these common Nigerian food wastes
are within the range of values from conventional feedstock. This makes them
suitable candidates for anaerobic digestion feedstock. Nonetheless actual
biogas yields will be lower than their theoretical values due to the presence of
non-degradable material and the consumption of 3-10% of the substrates by the

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11 microbes for growth (VDI 4630, 2006). The nine food wastes fall into the
12 category of plant based feedstock with Drosig et al (2013) reporting that the
13 actual yields of such plant-based feedstock are 50-70% of their theoretical
14 values. Longjan and Dehouche (2017) showed that the bioenergy yields of
15 some common Nigerian food wastes ranged from 69 to 76% of their theoretical
16 values.
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22 Comparing the study's results with fresh weight biogas yields reported by
23 Korres et al (2013), egusi shell and groundnut husk had higher potentials than
24 barley, rye, sugar beet and rice straw which ranged from 0.2 – 0.3 m³ kg⁻¹. The
25 tubers in this study were the closest group to this lower range of yields. Egusi
26 shell and groundnut husk had yields that were within the range of 0.4 – 0.5 m³
27 kg⁻¹ of paper co-digested with chicken manure.
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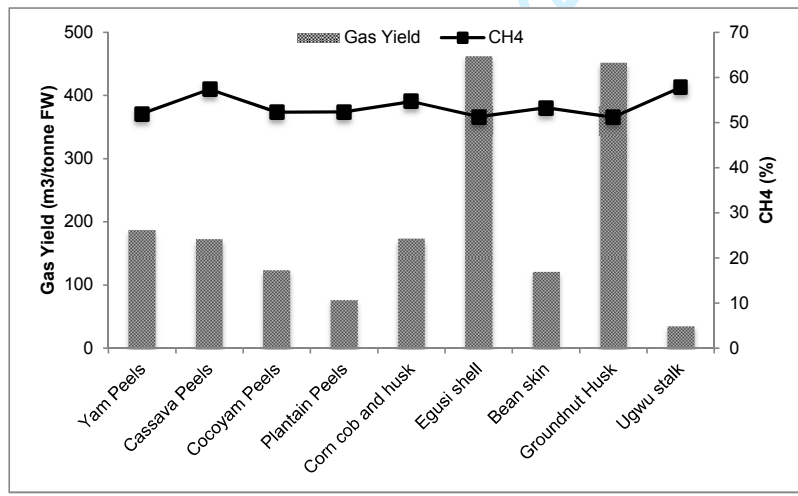
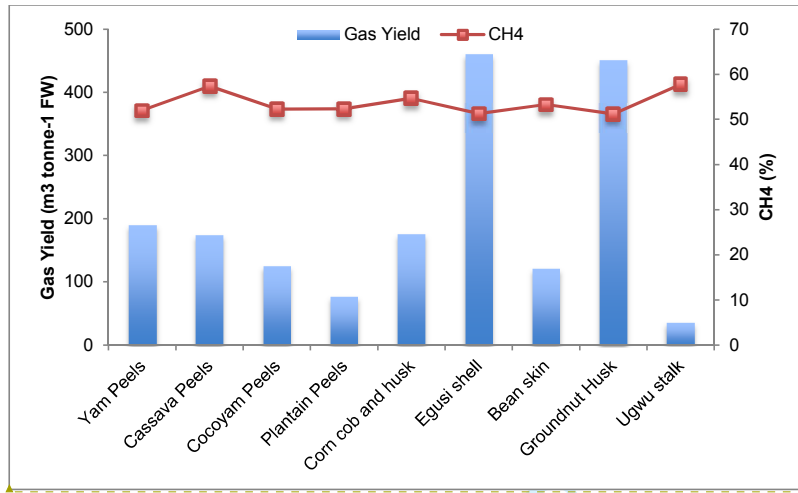


Figure 3. Bio-methane Potential of nine Nigerian food wastes on a Volatile Solid (VS) and Fresh Weight (FW) basis.

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11 ~~Comparing the study's results with fresh weight biogas yields reported by~~
12 ~~Korres et al (2013), egusi shell and groundnut husk had higher potentials than~~
13 ~~barley, rye, sugar beet and rice straw which ranged from 0.2–0.3 m³ kg⁻¹. The~~
14 ~~tubers in this study were the closest group to this lower range of yields. Egusi~~
15 ~~shell and groundnut husk had yields that were within the range of 0.4–0.5 m³~~
16 ~~kg⁻¹ of paper co-digested with chicken manure.~~

Regional Waste and Energy Potential

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26 The waste quantification results were presented for eight out of the nine food
27 foods-crops because production data could not be obtained for uguwu leaves.

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29 Cassava had the highest waste potential at 1.0×10^7 tonnes yr⁻¹ while egusi
30 had the lowest potential of 9.4×10^4 tonnes yr⁻¹. The regional waste potential
31 from the eight foods-crops is 3.0×10^7 tonnes yr⁻¹. The annual waste potentials
32 from the common Nigerian foods-crops are presented in Table 3.

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37 ~~In the UK, research by WRAP (2009) showed that at the household level,~~
38 ~~unavoidable wastes from fruits and vegetables totalled 5.2 and 2.5 (10⁵ tonnes~~
39 ~~yr⁻¹) respectively. These two food groups are in the same category as the~~
40 ~~wastes in this study. Their research also showed that other root vegetables,~~
41 ~~which are in the same category as the tubers in this study, produced a total of~~
42 ~~2.3×10^4 tonnes yr⁻¹ of unavoidable waste. This is far lower than the output~~

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11 ~~from the tubers in this study, which total 2.1×10^7 tonnes yr^{-1} . Bananas, which~~
12 ~~are similar to plantains, produced 2.3×10^5 tonnes yr^{-1} of waste in the UK,~~
13 ~~which is less than 9.5×10^5 tonnes yr^{-1} of potential plantain waste for Nigeria. In~~
14 ~~the UK corn produced 1.8×10^4 tonnes yr^{-1} of waste, which is far lower than the~~
15 ~~6.2×10^6 tonnes yr^{-1} potential corn waste of Nigeria. Beans produced 6.0×10^3~~
16 ~~tonnes yr^{-1} of waste in the UK, which is far lower than the 6.9×10^5 tonnes yr^{-1}~~
17 ~~of beans for this study. The highest amount of unavoidable food waste in the~~
18 ~~UK was tea waste at 3.7×10^5 tonnes yr^{-1} .~~

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26 ~~The high variability between the results from Nigeria and the UK is due to~~
27 ~~differences in food preference. Another factor is that in the Nigeria, food is~~
28 ~~predominantly prepared from its raw form, whereas in the UK, foods are bought~~
29 ~~already processed with little to no waste.~~

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34 The projected methane yield from food waste in Nigeria is $30 \times 10^8 \text{ m}^3 \text{ yr}^{-1}$. The
35 total renewable energy to be derived from that methane would be 31 TWh yr^{-1} .

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37 The bioenergy potentials of each food sample were calculated and are
38 presented in Table 3. An analysis of the energy contribution of each food waste
39 to ~~the energy mix~~bioenergy production shows that cassava contributes the
40 most to the energy ~~mix~~production at 35% while the least contribution is from
41 egusi at less than 1%. The contribution of each waste ~~to the energy mix~~ is
42 presented in Figure 4. The projected maximum electricity demand of Nigeria for

2020 at 7% growth is 398.5 TWh yr⁻¹ (REMP, 2012). The potential clean energy from the food waste in this study is 31 TWh yr⁻¹, which would meet 7.8% of the 2020 projected power demand.

Table 3. Waste and Renewable Energy Potential of common Nigerian food crops.

Food	Production ¹ (10 ⁶ tonnes)	Food Waste (10 ⁶ tonnes)	Methane Potential (10 ⁸ m ³)	Energy Potential (10 ⁹ kWh)
Yam	40.5	10.2	10.0	10.6
Cassava	53.0	10.5	10.4	11.0
Cocoyam	3.5	0.8	0.5	0.6
Plantain	2.8	0.9	0.4	0.4
Corn	10.4	6.2	5.9	6.2
Egusi	0.5	0.1	0.2	0.2
Bean	2.9	0.7	0.4	0.5
Groundnut	3.0	0.7	1.7	1.8
Total	-	30.2	29.6	31.2

¹ Source: (FAOSTAT, 2015)

~~The projected maximum electricity demand of Nigeria for 2020 at 7% growth is 398.5 TWh yr⁻¹ (REMP, 2012). The potential clean energy from the food waste in this study is 31 TWh yr⁻¹, which would meet 7.8% of the 2020 projected power demand.~~ When considering the long-term projections (2021-2030) for electricity from biomass of 0.9 TWh yr⁻¹ (REMP, 2012), that projection would be surpassed by 3,367%. Considering more recent statistics, the potential bioenergy of this study is 1.1 times the total generated electrical energy in Nigeria for 2014, which was 29.7 TWh (GOPA, 2015). Based on Nigeria's electricity consumption per household of 655 kWh yr⁻¹ (WEC, 2016), the bioenergy of this study would meet up to the demand of 4.7×10^7 households.

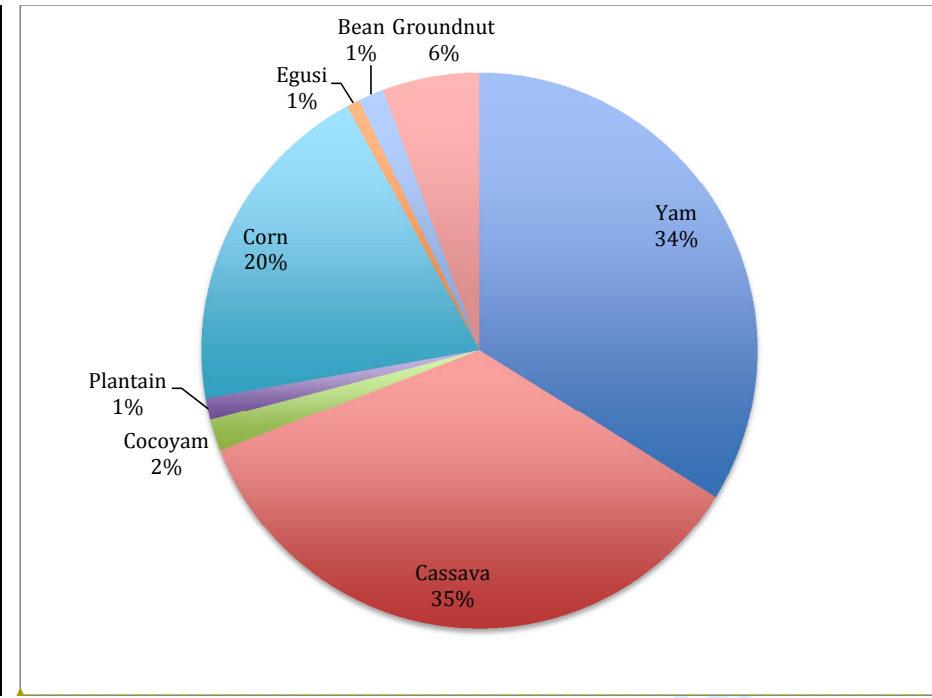
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11 Using the Nigerian per capita electricity consumption of 142 kWh yr⁻¹ (World
12 Bank, 2016), the food waste would provide energy that would meet the
13 consumption of 2.2×10^8 individuals.
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16 The estimated energy from AD in this study is far higher than the total electricity
17 from AD in the UK in 2014, which was 1.9 TWh (DEFRA, 2016) and also higher
18 than the energy from biodegradable waste in the UK which was 1.9 TWh.
19 Germany a leader in the renewable energy sector, attained 56.6 TWh of
20 electricity from Bioenergy (Burger, 2016) which was far higher than that of the
21 UK at 29.01 TWh (DECC, 2016). The potential Nigerian food waste is higher
22 than that of the UK, where food and drink waste from households were 7 million
23 tonnes (DEFRA, 2016).
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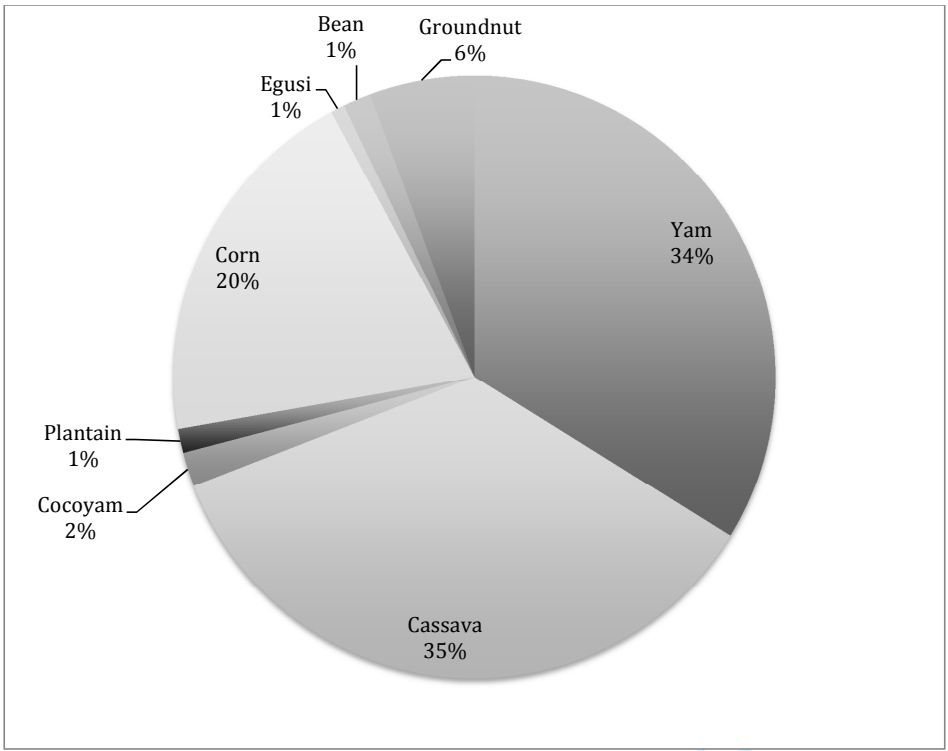


Figure 4. Potential Renewable Energy Mix contributions of common Nigerian food wastes showing their various contributions.

~~The estimated energy from AD in this study is far higher than the total electricity from AD in the UK in 2014, which was 1.9 TWh (DEFRA, 2016) and also higher than the energy from biodegradable waste in the UK which was 1.9 TWh. Germany a leader in the renewable energy sector, attained 56.6 TWh of electricity from Bioenergy (Burger, 2016) which was far higher than that of the UK at 29.01 TWh (DECC, 2016). The potential Nigerian food waste is higher than that of the UK, where food and drink waste from households were 7 million tonnes (DEFRA, 2016).~~

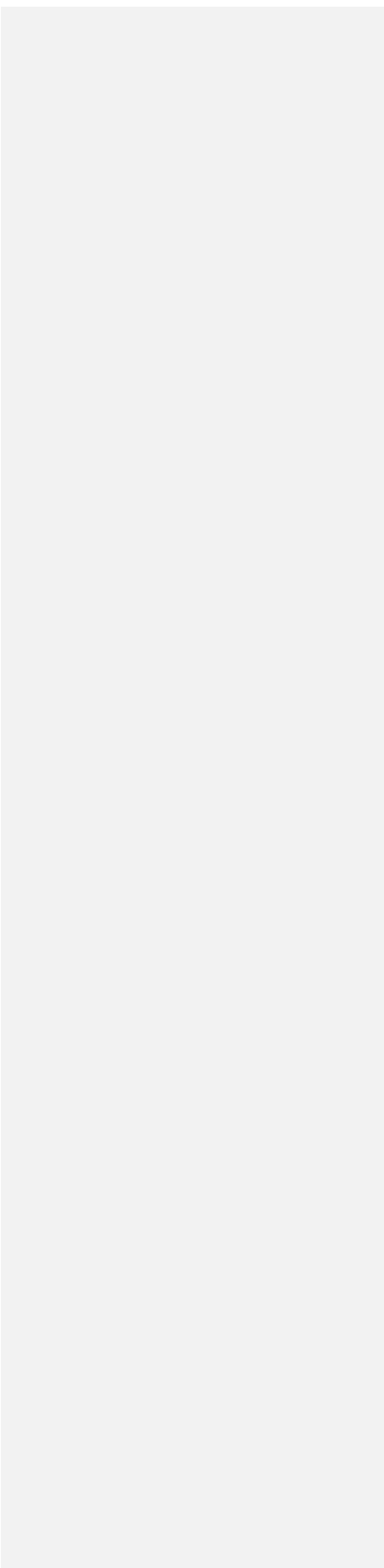
Conclusion

Nigeria is a leading producer of a wide range of food crops. Nine of these foods-crops were analysed for their waste potential. They showed a wide range of Specific Waste Indexes of 0.2 – 1.5. Their food wastes were characterized and their nutrient profiles showed large variations in crude fibres, proteins, oils and nitrogen free extracts. Their theoretical bio-methane potential varied widely with results ranging from 35 - 460 m³ tonne⁻¹ on a Fresh Weight basis and (5.4 – 6.2) x 10⁵ m³ kg⁻¹ on a Volatile Solid basis. The values were within the acceptable range of currently utilised AD feedstock. The combined wastes have a renewable energy potential of 31 TWh yr⁻¹ which could meet up to the energy demand of 4.7 × 10⁷ Nigerian households. The results indicate that common

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Nigerian food crops produce wastes that are suitable as feedstock in the anaerobic digestion process. These wastes have the potential to significantly complement the energy production of the country. Further research will be required to determine the actual biogas yields of these feedstocks.

For Peer Review



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Appendix 1: Baserga Model Equations

Digestibility factors:

<i>Crude Fibre</i>	(C_rFd)	74.3%
<i>Crude Protein</i>	(C_rPd)	65.09%
<i>Crude Fat</i>	$(OAHd)$	67.51%
<i>NFE</i>	$(NFEd)$	69.97%

Gas Yield Conversion Factors:

<i>Carbohydrates</i>	$(GYCf)$	790 l kg ⁻¹
<i>Proteins</i>	$(GYPf)$	700 l kg ⁻¹
<i>Fat</i>	$(GYOf)$	1250 l kg ⁻¹

Methane content of Biogas:

<i>Carbohydrates</i>	(Mcf)	50%
<i>Proteins</i>	(MPf)	71%
<i>Fats</i>	(Mof)	68%

Calculated Parameters

$$NFE = 100 - (C_rP + C_rF + OAH + Ash + Moisture)$$

$$VS = (C_rF + C_rP + OAH + NFE)$$

Baserga Equations:

$$\text{Digestible Carbohydrate } \left(\frac{g}{kg} DMB\right) DC = ((C_rF \times C_rFd) + (NFE \times NFEd))/10$$

$$\text{Digestible Crude Protein } \left(\frac{g}{kg} DMB\right) DP = (C_rP \times C_rPd)/10$$

$$\text{Digestible Crude Fat } \left(\frac{g}{kg} DMB\right) DO = (OAH \times OAHd)/10$$

And :

$$\text{Digestible Carbohydrate } \left(\frac{kg}{kg} VS\right) DCv = DC/(VS \times 10)$$

$$\text{Digestible Crude Protein } \left(\frac{kg}{kg} VS\right) DPv = DP/(VS \times 10)$$

$$\text{Digestible Crude Fat } \left(\frac{kg}{kg} VS\right) DOv = DO/(VS \times 10)$$

And :

$$\text{Gas Yield Carbohydrate } \left(\frac{l}{kg} VS\right) GYC = DCv \times GYCf$$

$$\text{Gas Yield Proteins } \left(\frac{l}{kg} VS\right) GYP = DPv \times GYPf$$

$$\text{Gas Yield Fat } \left(\frac{l}{kg} VS\right) GYO = DOv \times GYOf$$

$$\text{Total Gas Yield } \left(\frac{l}{kg} VS\right) TGY = GYC + GYP + GYO$$

And :

$$\text{Methane Share for Carbohydrates (\%)} MC = GYC \times MCf/TGY$$

$$\text{Methane Share for Protein (\%)} MP = GYP \times MPf/TGY$$

$$\text{Methane Share for Fats (\%)} MO = GYO \times MOf/TGY$$

$$\text{Total Methane Content (\%)} TMC = MC + MP + MO$$

And :

$$\text{Gas Yield } \left(\frac{m^3}{tonne}\right) \text{ of Fresh Matter} = (TGY \times VS)/100$$

Appendix 2: Calculations for Waste Quantification and Renewable Energy Potential of Nigeria

The following calculations were used to obtain the Waste and Renewable Energy Potentials of common Nigerian food crops.

Calculations:

Annual Food Waste (Tonnes) = Annual Food Production (Tonnes) × Waste Content of food (%)

Annual Biogas Potential (m³) = Annual Food Waste (tonnes) × BioMethane Potential of Food Waste (m³/tonne)

Annual Methane Potential (m³) = Annual Biogas Potential (m³) × Methane Content (%)

Annual Energy Potential (MJ) = Annual Methane Potential (m³) × Gross Calorific Value Methane (MJ/m³)

Annual Elect. Energy Potential (kWh/yr) = Annual Energy Potential (MJ) × 0.2778 kWh/MJ

Constants

Gross Calorific Value Methane = 38 MJ/m³

1 MJ = 0.2778 kWh

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