Nutrient Characterisation and Bioenergy Potential of Common Nigerian Food Wastes

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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 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.

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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 m^3 $tonne^{-1}$ on Fresh Weight and (5.4 – 6.2) x 10^5 m^3 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 4.7×10^7 Nigerian households. Further studies would be required to determine the actual biogas yields of the food wastes.

Keywords

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

Introduction

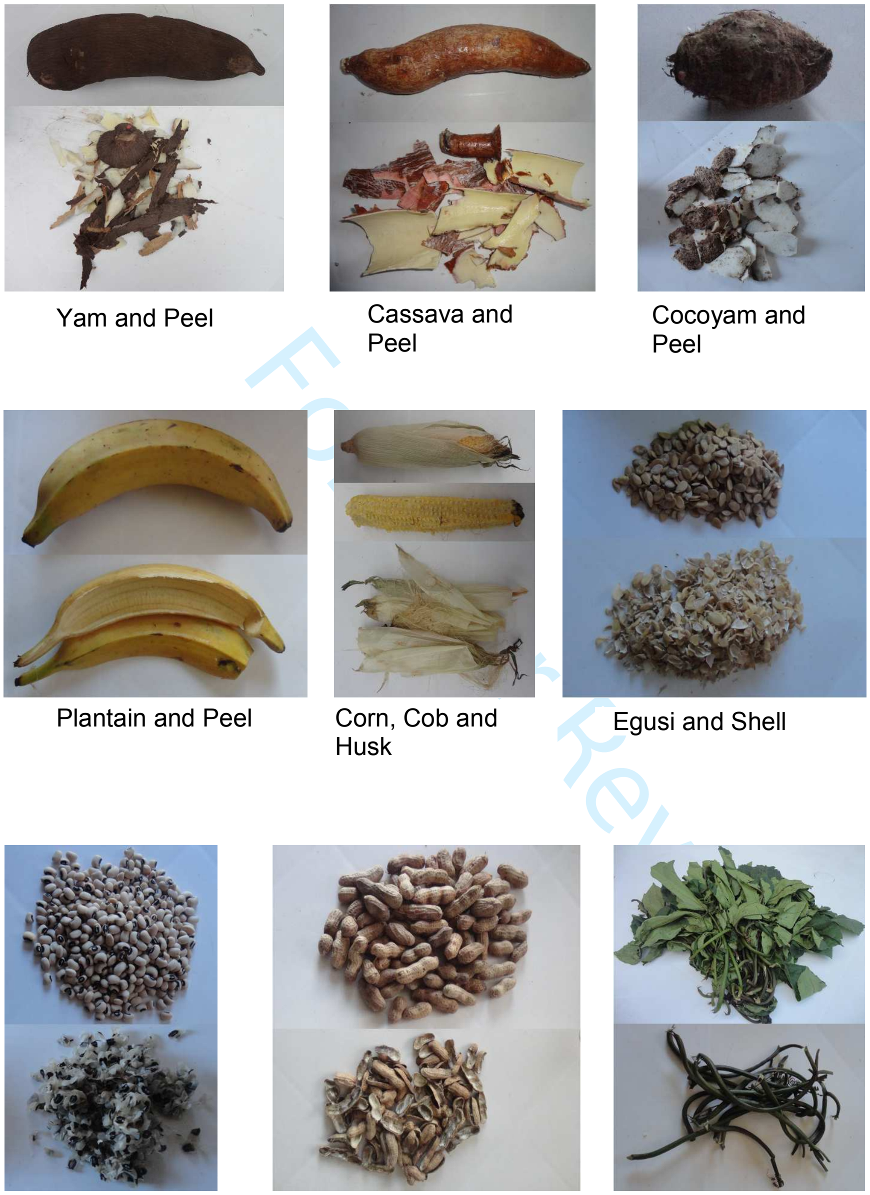
Renewable technologies allow the current energy demand to be met without compromising the ability of future generations to meet their own energy needs. There has been extensive research in this field in developed countries while developing nations are yet to fully embrace these technologies. One of such 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).

The first step in analysing the suitability of an organic waste product for use as an AD feedstock is its nutrient characterisation. The vast varieties of possible feedstock for biogas production demonstrate the need for detailed characterisation of each potential feedstock (Drosg et al., 2013). Knowledge of the distribution of nutrients in a feedstock is required to determine its suitability as a prime biofuel (Steffan et al., 1998). The performance of feedstock in a digester can also be predicted with knowledge of the feedstock constituents. This information is obtained from the different digestion rates of various nutrients in digesters (Al Seadi et al., 2013). The availability of such data on feedstock can be used for a preliminary evaluation on the fitness of such materials as bioenergy raw material.

Nine potential AD feedstocks were selected from food crops that have high production values in Nigeria. These crops are Yam (*Dioscorea rotundata* Poir.), Cassava (*Manihot esculenta* Crantz), Cocoyam/Taro (*Colocasia esculenta* (L.) Schott), Plantain (*Musa paradisiaca* L.), Corn/Maize (*Zea mays* L.), Egusi/Melon Seed (*Citrullus colocynthis* (L.) Schrader), Beans/Cowpea (*Vigna unguiculata* (L.) Walp), Groundnut/Peanut (*Arachis hypogaea* L.) and Ugwu/Fluted Pumpkin Leaves (*Telfairia occidentalis* Hook). Among these crops, the FAOSTAT database (FAOSTAT, 2015) indicates that Nigeria is the world's largest producer of yam (4.0×10^7 tonnes yr^{-1}), cassava (5.3×10^7 tonnes yr^{-1}), cocoyam (3.5×10^6 tonnes yr^{-1}), egusi (5.1×10^5 tonnes yr^{-1}) and beans (2.9×10^6 tonnes yr^{-1}). Nigeria is also the third largest producer of groundnut (3.0×10^6 tonnes yr^{-1}) in addition to being a major producer of plantain (2.8×10^6 tonnes yr^{-1}) and corn (1.0×10^7 tonnes yr^{-1}). There was no production data on 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.



Yam and Peel; Cassava and Peel; Cocoyam and Peel

Plantain and Peel; Corn, Cob and Husk; Egusi and Shell

Beans and Skin; Groundnut and Shell; Ugwu and Stalk

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.

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 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.

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

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 the requirement for analytical chemistry procedures, the food waste samples were sent to NRM laboratories, Bracknell, UK for the waste characterisation. A brief description of the type of analyses that were performed is provided below.

Total Solids and Moisture Content

Total solid (TS) is the dry matter of a sample after all moisture has been completely removed. To measure the TS, the sample was dried in an oven to a constant weight at $105^{O}C$. The weight of the residue is the TS content of the sample. The moisture content was obtained from subtracting the weight of the TS from the initial weight of the sample.

Volatile Solids and Ash Content

Volatile Solids (VS) are the components of a sample that are lost on ignition at $550^{O}C$. To measure the VS, the sample is dried to constant weight in an oven at $105^{O}C$. After drying, the sample is weighted then placed in a furnace and ignited at $550^{O}C$ for four hours. The residue is then taken out of the furnace and weighted. The residue is the Ash Content of the sample while the difference in weight between the initial dry mass and the residue is the VS content.

Crude Fibre

Crude Fibre (CrF) is the complex carbohydrate 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% H_2SO_4 and 1.25% NaOH solutions. The sample was placed in a flask and the H_2SO_4 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 a sample. It can also refer to the free lipid content. The analysis method involves the fats being extracted from the sample with petroleum ether and evaluated as a percentage of the weight before the solvent is evaporated.

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 bioenergy potential of the crops. The equations used for the calculations are presented in Appendix 2.

Statistical Analyses

The statistical analyses that were performed on the results are presented in this section. The analyses were performed using computer programmes, specifically IBM SPSS Statistics 23 and Microsoft Excel for Mac 2011.

Kruskal-Wallis Test

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

Dunn's Test

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

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%. Ugwu 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%.

The seed has a low moisture content leading to dry and lightweight shells. The TWC of beans was 23% and consisted of moisture from its processing method. The results show that crops like corn, plantain and ugwu can have high TWC but the wastes will consist of low organic fractions. However crops like egusi and groundnut have low TWC, but high organic proportions.

The results of Russ and Meyer-Pittroff (2004) showed that the only food whose SWI was greater than 1.0 was cheese, whose values got up to 11 for whey waste as a result of its processing method. None of the samples of this study obtained an SWI value as high as 2.0. Foods with high SWI are ideal for feedstock that will be considered in the anaerobic digestion chain. If SWI is the only factor, corn produces the best results. However if the organic content of the food waste has to be considered, then egusi is the ideal choice. The implication is that both factors have to be considered when selecting an appropriate food for its waste.

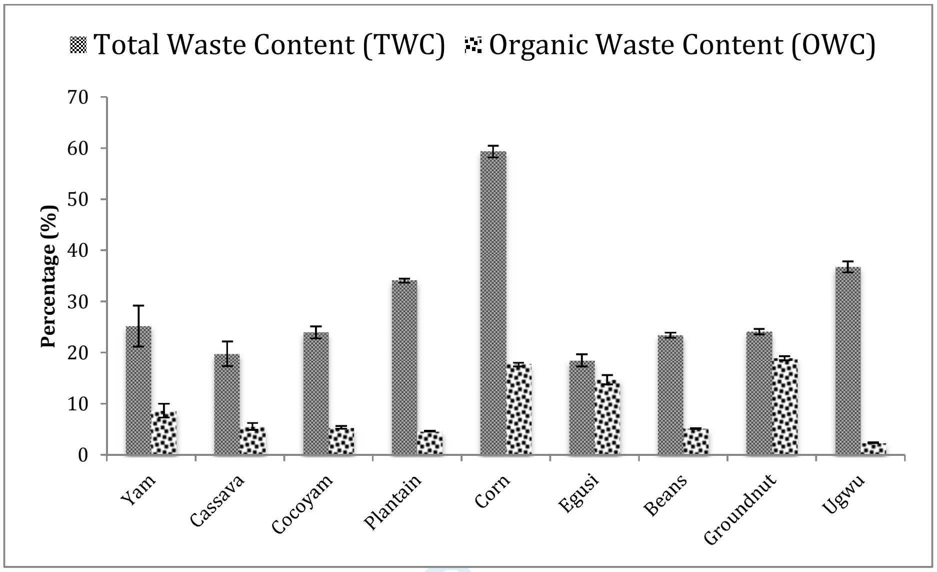


Figure 2. Waste content of nine Nigerian food crops showing the Total Waste Content (TWC) and Organic Waste Content (OWC). (Error bars indicating relative error of measurement).

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.

Plantain was significantly different from Cassava. Corn was significantly different from Yam, Cassava and Cocoyam. Egusi was significantly different from Plantain and Corn. Beans was significantly different from Corn. While Ugwu was significantly different from Cassava and Egusi.

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 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 m^3 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 - 97%. The results were within the range of VS/TS for plant wastes as reported by Al Seadi et al (2013) and higher than the 70-80% for energy crops as reported by Neureiter (2013). Common biodegradable organic matter should have a VS/TS of at least 70% while feedstocks with lower than 60% VS/TS are not suitable as feedstock for the AD process (Steffen et al., 1998). Ugwu stalk had the lowest VS/TS contents at 87% but was still within the acceptable values for AD feedstock. The VS content of a feedstock can be useful in bioenergy estimations but it does not give information on the digestibility of the sample (Drosg et al., 2013).

The yam peel TS content was higher than the values obtained by (Ojikutu and Osokoya, 2014; Makinde and Odokuma, 2015; Heiske et al, 2015) which ranged from 19% to 23% TS. For cassava peel, the TS of 29% and VS/TS of 96% were within the ranges of 25 - 35% TS and 90 - 97% VS/TS reported by (Cuzin et al., 1992; Jekayinfa and Scholz, 2013). For the cocoyam peel, the 24% TS and 91% VS/TS was close to the 27% TS and 92% VS/TS obtained by Adeyosoye et al. (2010) while for plantain peel, the low values for TS of 15%

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 ugwu stalk and plantain peel each below 2% FW. Jekayinfa and

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

Theoretical Biogas Potential

The Bio-Methane Potential analysis, performed using the Baserga Model equations detailed in Appendix 1, showed a narrow range of (5.4 – 6.2) x 10^5 m^3 kg^{-1} VS for biogas yields. The potential methane content varied between 51 – 58%. These values are in the range of grain yields as reported in (NNFCC, 2016).

The biogas potentials for the fresh weight (FW) of the sample took into consideration the moisture content of the food waste. In this category, there was a high variation in potential yield, ranging from 0.04 – 0.50 m^3 kg^{-1} FW with an average potential of 0.2 m^3 kg^{-1} FW. The highest potential yields were from the egusi shell and groundnut husk at 0.5 m^3 kg^{-1} FW each. They also had the lowest methane potential of 51% each. The lowest biogas potential in this category was from the ugwu stalk with a value of 0.04 m^3 kg^{-1} FW but had the highest methane potential of 58%. The theoretical biogas yields on the volatile solid and fresh weight basis are presented in Figure 3. Cassava peel had the highest biogas potential on VS basis and second highest methane potential. On a fresh weight basis it has the fifth highest potential. Its high moisture content at 71% leads to a low nutrient concentration in the digester leading to lower energy output. The low moisture contents of egusi shell and groundnut husk at 18 and 19% respectively, allow them to have the highest fresh weigh yields.

The range of results for biogas potentials on a volatile solid basis corresponds to a wide variety of feedstock found in literature. Feedstock with similar yields include vegetable waste, potato waste, food waste, fruit waste, slaughterhouse waste and household waste as reported by (Deublein and Steinhauser, 2011). 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 microbes for growth (VDI 4630, 2006). The nine food wastes fall into the category of plant based feedstock with Drosg et al (2013) reporting that the actual yields of such plant-based feedstock are 50-70% of their theoretical values. Longjan and Dehouche (2017) showed that the bioenergy yields of some common Nigerian food wastes ranged from 69 to 76% of their theoretical values.

Comparing the study's results with fresh weight biogas yields reported by Korres et al (2013), egusi shell and groundnut husk had higher potentials than barley, rye, sugar beet and rice straw which ranged from 0.2 – 0.3 m^3 kg^{-1}. The tubers in this study were the closest group to this lower range of yields. Egusi shell and groundnut husk had yields that were within the range of 0.4 – 0.5 m^3 kg^{-1} of paper co-digested with chicken manure.

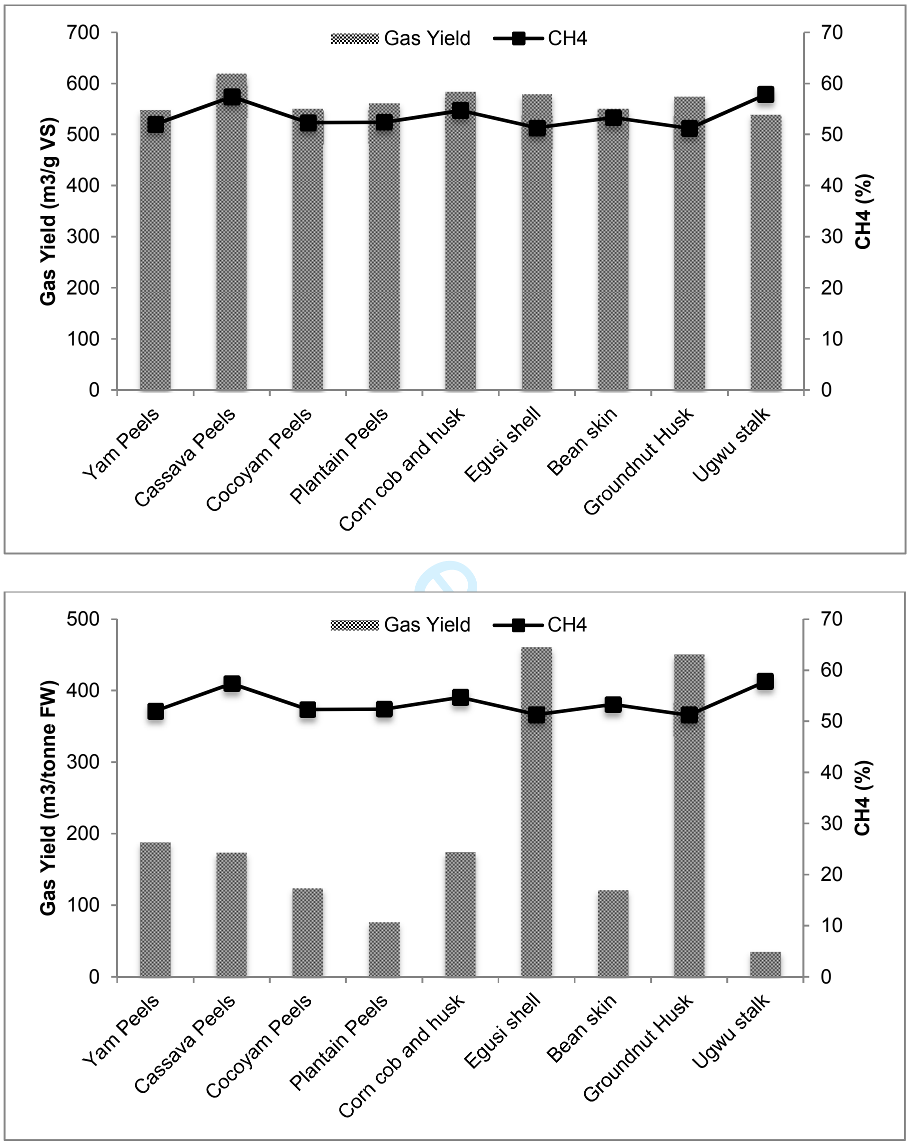


Figure 3. Bio-methane Potential of nine Nigerian food wastes on a Volatile Solid (VS) and Fresh Weight (FW) basis.

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 × 10^{8} m^{3} 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 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).

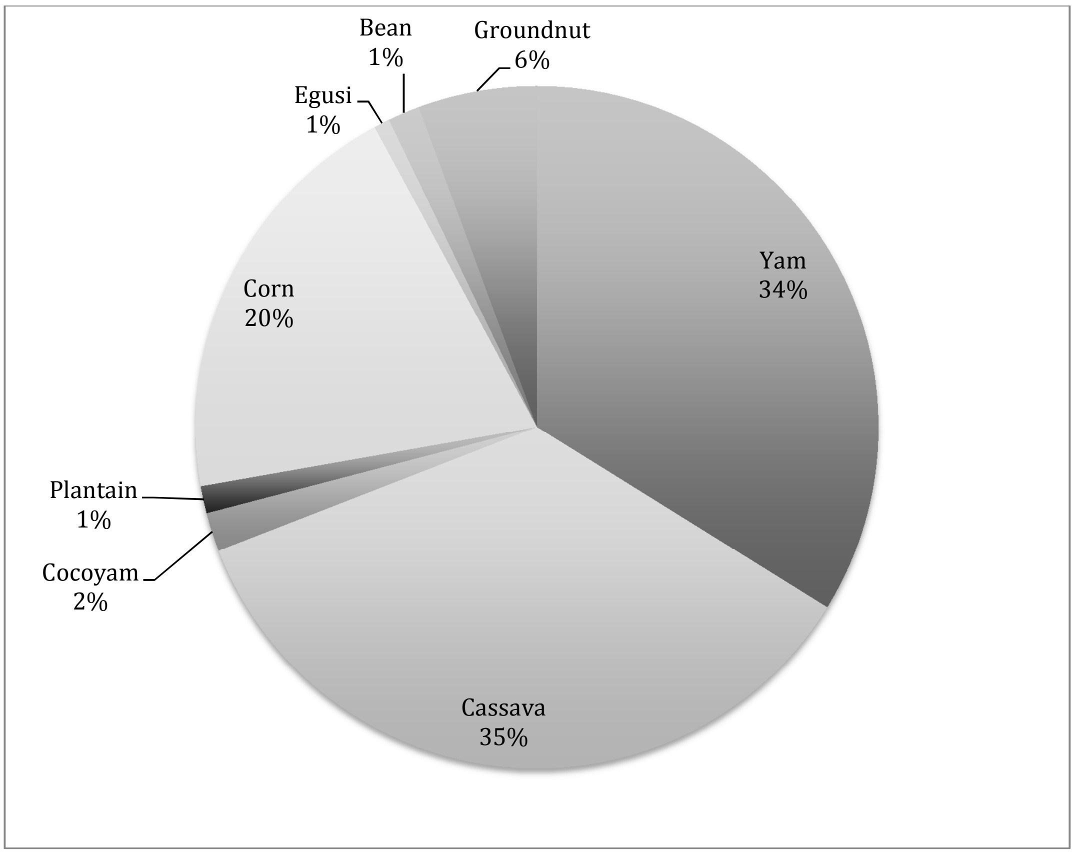


Figure 4. Potential Renewable Energy contributions of common Nigerian food wastes.

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 m^3 $tonne^{-1}$ on a Fresh Weight basis and (5.4 – 6.2) x 10^5 m^3 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 × 10^7 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:

Crude Fibre	(C_rFd)	*74.3%*
Crude Protein	(C_rPd)	*65.09%*
Crude Fat	(*OAHd*)	*67.51%*
NFE	(*NFEd*)	*69.97%*

Gas Yield Conversion Factors:

Carbohydrates	(*GYCf*)	*790 l kg*$^{-1}$
Proteins	(*GYPf*)	*700 l kg*$^{-1}$
Fat	(*GYOf*)	*1250 l kg*$^{-1}$

Methane content of Biogas:

Carbohydrates	(*MCf*)	*50%*
Proteins	(*MPf*)	*71%*
Fats	(*Mof*)	*68%*

Calculated Parameters

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

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

Baserga Equations:

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

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

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

And :

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

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

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

And :

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

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

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

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

And :

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

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

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

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

And :

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

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 (m^3) = Annual Food Waste (tonnes) × BioMethane Potential of Food Waste (m^3/tonne)

Annual Methane Potential (m^3) = Annual Biogas Potential (m^3) × Methane Content (%)

Annual Energy Potential (MJ) = Annual Methane Potential (m^3) × Gross Calorific Value Methane (MJ/m^3)

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

Constants

Gross Calorific Value Methane = 38 MJ/m^3

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 cropss 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 Aanaerobic Ddigestion 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 Modelappropriate 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 m^3 $tonne^{-1}$ on Fresh Weight and (5.4 – 6.2) x 10^5 m^3 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}

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

Keywords

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

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 A~~a~~naerobic D~~d~~igestion (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).

The first step in analysing the suitability of an organic waste product for use as an AD feedstock is its nutrient characterisation. The vast varieties of possible feedstock for biogas production demonstrate the need for detailed characterisation of each potential feedstock (Drosg et al., 2013). Knowledge of the distribution of nutrients in a feedstock is required to determine its suitability as a prime biofuel (Steffan et al., 1998). The performance of feedstock in a digester can also be predicted with knowledge of the feedstock constituents. This information is obtained from the different digestion rates of various nutrients in digesters (Al Seadi et al., 2013). The availability of such data on feedstock can be used for a preliminary evaluation on the fitness of such materials as bioenergy raw material.

Nine potential AD feedstocks were selected from food crops~~s~~ that have high production values in Nigeria. The~~ food items ~~se crops are Yam (*Dioscorea rotundata* Poir.), Cassava (*Manihot esculenta* Crantz), Cocoyam/Taro (*Colocasia esculenta* (L.) Schott), Plantain (*Musa paradisiaca* L.), Corn/Maize (*Zea mays* L.), Egusi/Melon Seed (*Citrullus colocynthis* (L.) Schrader), Beans/Cowpea (*Vigna unguiculata* (L.) Walp), Groundnut/Peanut (*Arachis hypogaea* L.) and Ugwu/Fluted Pumpkin Leaves (*Telfairia occidentalis* Hook). Among these crops~~food items~~, the FAOSTAT database (FAOSTAT, 2015) indicates that Nigeria is the world’s largest producer of yam (4.0 × 10^7 tonnes yr^{-1}), cassava (5.3 × 10^{7} tonnes yr^{-1}), cocoyam (3.5 × 10^{6} tonnes yr^{-1}), egusi (5.1 × 10^{5} tonnes yr^{-1}) and beans (2.9 × 10^{6} tonnes yr^{-1}). Nigeria is also the third largest producer of groundnut (3.0 × 10^{6} tonnes yr^{-1}) in addition to being a major producer of plantain (2.8 × 10^{6} tonnes yr^{-1}) and corn (1.0 × 10^{7} tonnes yr^{-1}). There was no production data on ugwu leaves possibly due to its localised consumption in Nigeria. These high quantities of food crops will produce equally high volumes of food waste, which can serve as raw materials for biofuel production. These common food cropss 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 cropsfoods as AD feedstock. This shall be accomplished by determining the waste content of each of the nine foodssamples 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 foodcropss commonlocal 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 cropss and their various waste products.

Materials and methods

Sample Collection

The nine cropfood samples were locally sourced from Nigeria and transported to Brunel University London, UK. The waste fractions were extracted from the samplesfoods 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 wereare 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 wereare 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 hads 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. Thatis softeneds the skin which then easily comes came off when the beans wereare rubbed together using hands. Groundnut produces groundnut husk, that which wasis extracted by cracking the nut with fingers. The waste of ugwu is the ugwu stalk, which wasis 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.

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

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 the requirement for analytical chemistry procedures, the food waste samples were sent to NRM laboratories, Bracknell, UK for the waste characterisation. A brief description of the type of analyses that were performed is provided below.

Total Solids and Moisture Content

Total solid (TS) is the dry matter of a sample after all moisture has been completely removed. To measure the ~~total solids~~TS, the sample was~~is~~ dried in an oven to a constant weight at 105^{O}C. The weight of the residue ~~is then weighed and compared to the initial sample weight. The result~~ is the TS ~~total solid~~ content of the sample. The moisture content was~~is~~ obtained from subtracting the weight of the TS from the initial weight of the sample.

Volatile Solids and Ash Content

Volatile Solids (VS) are the ~~organic dry matter of a~~components of a sample that are lost on ignition at 550^{O}C, . To measure the VS, the sample is dried to constant weight in an oven at 105^{O}C. After drying, the sample is weighted then placed in a furnace and ignited ~~in a furnace~~ at 550^{O}C for four hours. The residue is then taken out of the furnace and weighted. The residue is the Ash Content of the sample while t~~T~~he difference in weight between the initial dry mass and the residue is the ~~volatile solid~~VS content.

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Crude Fibre

Crude Fibre~~s~~ (CrF) is~~are~~ the complex carbohydrate~~s~~ 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% H_2SO_4 and 1.25% NaOH solutions. The sample was~~is~~ placed in a flask and the H_2SO_4 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 a~~the~~ sample. It can also refer to the free lipid content. The analysis method involves the fats being extracted from the sample with petroleum ether and evaluated as a percentage of the weight before the solvent is evaporated.

Nitrogen Free Extract (NFE)

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

Ash

The Ash is the total mineral matter of a sample. To measure the value, a sample is dried to constant weight in an oven. After drying, the sample is weighed then placed in a furnace and ignited at 550^{o}C for four hours. The residue is then taken out of the furnace and weighed and the result indicates the ash content of the sample.

Moisture Content

The moisture content is the liquid component of a sample. To measure the moisture content, the sample is initially weighed. Next the sample is dried in an oven to a constant weight at 105^{o}C. The residue is then weighed and its weight is subtracted from the initial weight of the sample. The final result, which indicates the loss in weight, is the moisture content of the sample.

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 ~~foods~~crops. The equations used for the calculations are presented in Appendix 2.

Statistical Analys~~e~~is

The ~~various~~ statistical analyses that were performed on the results are presented in this section. The analyses were performed using computer programmes, specifically IBM SPSS Statistics 23 and Microsoft Excel for Mac 2011.

Kruskal-Wallis Test

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

Dunn's Test

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

Results and Discussion

Specific Waste Index and Waste Content of food

The results of the Specific Waste Index (SWI) analysis of the food samplescrops showed an SWI range of 0.2 – 1.5 for the nine foods 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 W~~w~~aste C~~c~~ontent (TWC) and the Organic Waste Content (OWC)~~s~~ of each crop~~food~~ ~~and their waste organic content (OWC/TWC)~~ are displayed in Figure 2. The TWC indicates the proportion of the crop that is non-consumable. T~~T~~he OWC indicates the ~~amount of waste in the food that is organic in composition~~ organic fraction of the non-consumable part of the crop in proportion to the whole crop. The average ~~total waste content~~TWC of the nine ~~food items~~samples is 29% while the average ~~organic waste content~~OWC of the foods is 9%. Corn had the highest ~~waste content~~TWC of 59% from the husk and cob. The corn ~~wastes~~ TWC has~~ve~~ a low organic content of 30%. Ugwu had the second highest ~~waste content~~TWC of 37% with the lowest ~~organic waste content~~OWC of 2%. The lowest ~~waste content~~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 ~~organic waste content~~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 ~~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 itemcrop, so the waste's proportions are uniform.

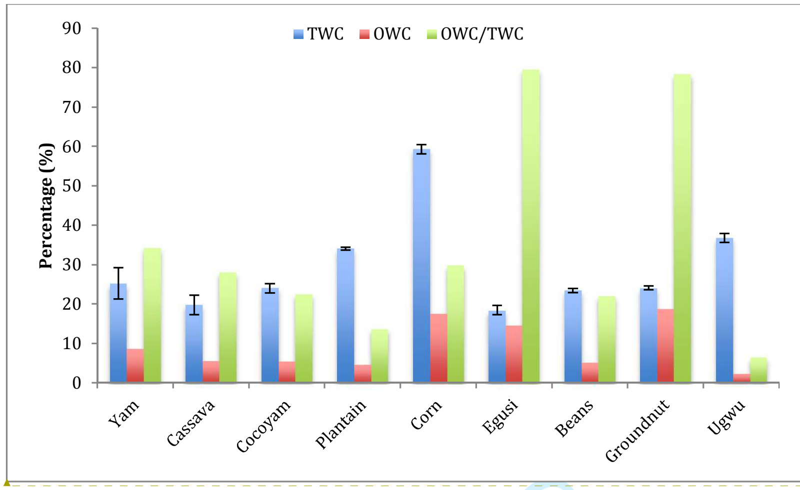
Table 1. Specific Waste Index of nine common Nigerian food cropss.

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 wasteTWC with a value of 19%. The seed has a low moisture content leading to dry and lightweight shells. The total waste contentTWC of beans was 23% and consisted of moisture from its processing method. The results show that ~~foods~~ crops like corn, plantain and ugwu can have high ~~waste contents~~TWC but the wastes will consist of low organic fractions. However ~~foods~~ crops like egusi and groundnut have low ~~waste contents~~TWC, but high organic proportions.

The results of ~~(~~Russ and Meyer-Pittroff~~,~~ (2004) showed that the only food whose SWI was greater than 1.0 was cheese, whose values got up to 11 for whey waste as a result of its processing method. None of the samples of this study obtained an SWI value as high as 2.0. Foods with high SWI are ideal for feedstock that will be considered in the anaerobic digestion chain. If SWI is the only factor, corn produces the best results. However if the organic content of the food waste has to be considered, then egusi is the ideal choice. The implication is that both factors have to be considered when selecting an appropriate food for its waste.



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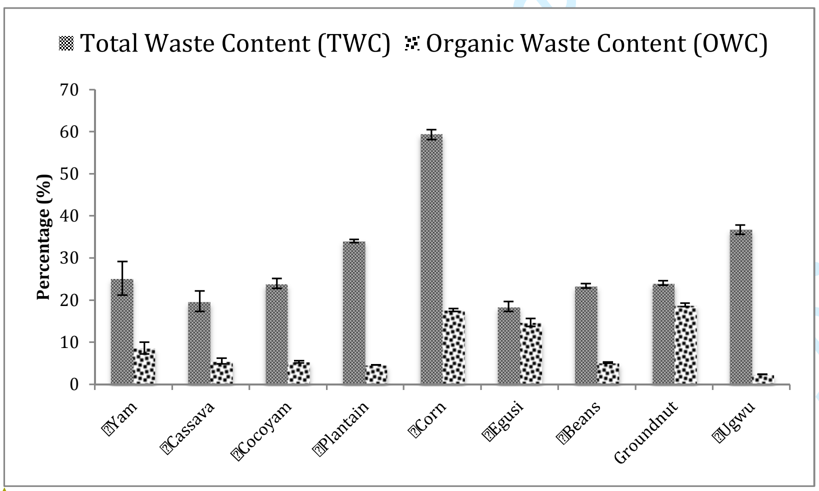

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Figure 2. Waste content of nine Nigerian food cropss showing the Total Waste Content (TWC) and , Organic Waste Content (OWC). and the relationship

between OWC and TWC (ETWC error bars indicating relative error of measurement).

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

A non-parametric Kruskal-Wallis test was performed on the waste analysis results to determine if there was any significant difference between the waste content of the samplesdifferent foodscrops. 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. Plantain was significantly different from Cassava. Corn was significantly different from Yam, Cassava and Cocoyam. Egusi was significantly different from Plantain and Corn. Beans was significantly different from Corn. While Ugwu was significantly different from Cassava and Egusi. The statistical analyses were performed using the SPSS IBM software 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 ~~foods~~ 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 m^3 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 -

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

The yam peel TS content was higher than the values obtained by (Ojikutu and Osokoya, 2014; Makinde and Odokuma, 2015; Heiske et al, 2015) which ranged from 19% to 23% TS. For cassava peel, the TS of 29% and VS/TS of 96% were within the ranges of 25 - 35% TS and 90 - 97% VS/TS reported by (Cuzin et al., 1992; Jekayinfa and Scholz, 2013). For the cocoyam peel, the 24% TS and 91% VS/TS was close to the 27% TS and 92% VS/TS obtained by Adeyosoye et al. (2010) while for plantain peel, the low values for TS of 15% 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 SolidsVS/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 ExtractsFW = 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 ugwu 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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3% FW. High fibre feedstock can cause foaming and lignin incrustation in digesters. Cassava peel, with a large margin, had the highest oil content at 7% FW. This is due to cassava being covered in wax to prevent the tuber from decomposing (Booth, 1973; Knoth, 1993; Onyenwoke and Simonyan, 2014). Feedstock with high oil content leads to poor bioavailability and longer retention times (Steffen et al., 1998). Excess oils in feedstock can have a detrimental effect during digestion due to oils poor water solubility and ability to increase VFA levels leading to low digester pH. The yam peels had the highest NFE content while the lowest was the ugwu stalk. Groundnut husk had the highest ash content of 3% FW.

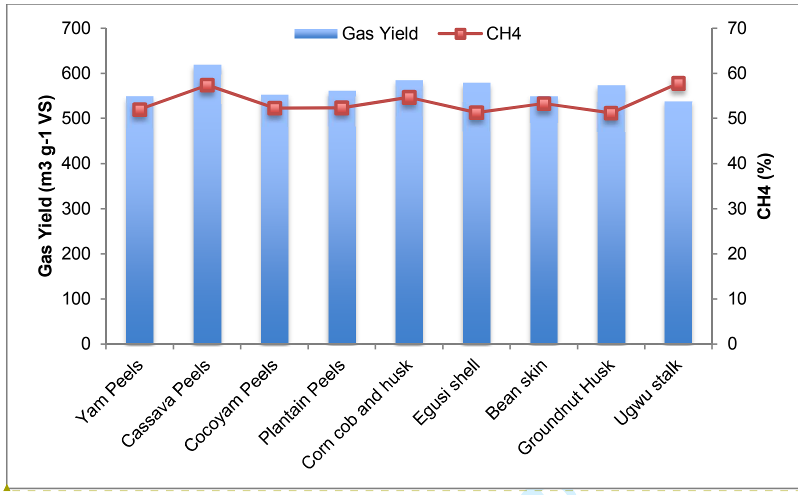
Theoretical Biogas Potential

The Bio-Methane Potential analysis, performed using the Baserga Model equations detailed in Appendix 1, showed a narrow range of (5.4 – 6.2) x 10^5 m^3 kg^{-1} VS for biogas yields. The potential methane content varied between 51 – 58%. These values are in the range of grain yields as reported in (NNFCC, 2016).

The biogas potentials for the fresh weight (FW) of the sample took into consideration the moisture content of the food waste. In this category, there was a high variation in potential yield, ranging from 0.04 – 0.50 m^3 kg^{-1} FW with an average potential of 0.2 m^3 kg^{-1} FW. The highest potential yields were from the egusi shell and groundnut husk at 0.5 m^3 kg^{-1} FW each. They also had the lowest methane potential of 51% each. The lowest biogas potential in this category was from the ugwu stalk with a value of 0.04 m^3 kg^{-1} FW but had the highest methane potential of 58%. The theoretical biogas yields on the volatile solid and fresh weight basis are presented in Figure 3. Cassava peel had the highest biogas potential on VS basis and second highest methane potential. On a fresh weight basis it has the fifth highest potential. Its high moisture content at 71% leads to a low nutrient concentration in the digester leading to lower energy output. The low moisture contents of egusi shell and groundnut husk at 18 and 19% respectively, allow them to have the highest fresh weigh yields.

The range of results for biogas potentials on a volatile solid basis corresponds to a wide variety of feedstock found in literature. Feedstock with similar yields include vegetable waste, potato waste, food waste, fruit waste, slaughterhouse waste and household waste as reported by (Deublein and Steinhauser, 2011). 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 microbes for growth (VDI 4630, 2006). The nine food wastes fall into the category of plant based feedstock with Drosg et al (2013) reporting that the actual yields of such plant-based feedstock are 50-70% of their theoretical values. Longjan and Dehouche (2017) showed that the bioenergy yields of some common Nigerian food wastes ranged from 69 to 76% of their theoretical values.

Comparing the study's results with fresh weight biogas yields reported by Korres et al (2013), egusi shell and groundnut husk had higher potentials than barley, rye, sugar beet and rice straw which ranged from 0.2 – 0.3 m^3 kg^{-1}. The tubers in this study were the closest group to this lower range of yields. Egusi shell and groundnut husk had yields that were within the range of 0.4 – 0.5 m^3 kg^{-1} of paper co-digested with chicken manure.



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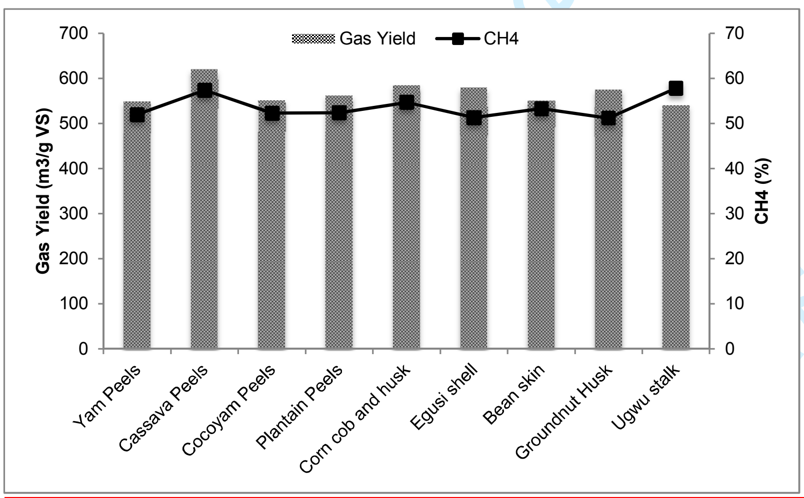

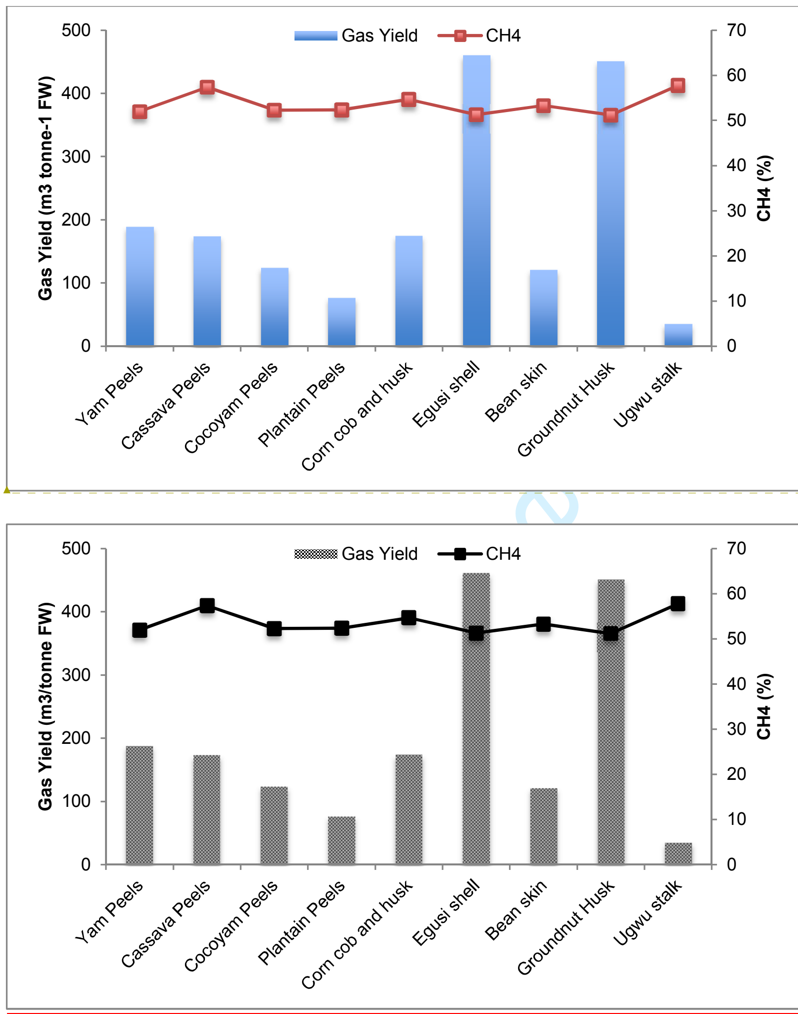

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Figure 3. Bio-methane Potential of nine Nigerian food wastes on a Volatile Solid (VS) and Fresh Weight (FW) basis.

Comparing the study's results with fresh weight biogas yields reported by Korres et al (2013), egusi shell and groundnut husk had higher potentials than barley, rye, sugar beet and rice straw which ranged from 0.2 – 0.3 m^3 kg^{-1}. The tubers in this study were the closest group to this lower range of yields. Egusi shell and groundnut husk had yields that were within the range of 0.4 – 0.5 m^3 kg^{-1} of paper co-digested with chicken manure.

Regional Waste and Energy Potential

The waste quantification results were presented for eight out of the nine food foods 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 foods crops is 3.0 × 10^7 tonnes yr^{-1}. The annual waste potentials from the common Nigerian foods crops are presented in Table 3.

In the UK, research by WRAP (2009) showed that at the household level, unavoidable wastes from fruits and vegetables totalled 5.2 and 2.5 (10^5 tonnes yr^{-1}) respectively. These two food groups are in the same category as the wastes in this study. Their research also showed that other root vegetables, which are in the same category as the tubers in this study, produced a total of 2.3 × 10^4 tonnes yr^{-1} of unavoidable waste. This is far lower than the output from the tubers in this study, which total 2.1× 10^7 tonnes yr^{-1}. Bananas, which are similar to plantains, produced 2.3 × 10^5 tonnes yr^{-1} of waste in the UK, which is less than 9.5 × 10^5 tonnes yr^{-1} of potential plantain waste for Nigeria. In the UK corn produced 1.8 × 10^4 tonnes yr^{-1} of waste, which is far lower than the 6.2 × 10^6 tonnes yr^{-1} potential corn waste of Nigeria. Beans produced 6.0 × 10^3 tonnes yr^{-1} of waste in the UK, which is far lower than the 6.9 × 10^5 tonnes yr^{-1} of beans for this study. The highest amount of unavoidable food waste in the UK was tea waste at 3.7 × 10^5 tonnes yr^{-1}.

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

The projected methane yield from food waste in Nigeria is 30 × 10^8 m^3 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 the energy mixbioenergy production shows that cassava contributes the most to the energy mix production at 35% while the least contribution is from egusi at less than 1%. The contribution of each waste to the energy mix 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~~s~~.

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)

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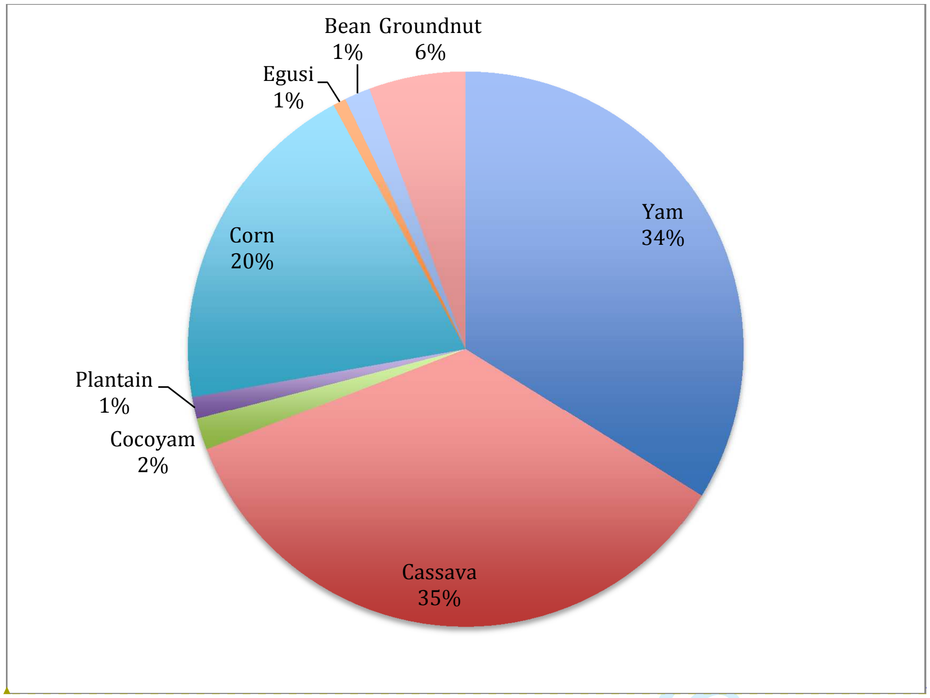
~~The projected maximum electricity demand of Nigeria for 2020 at 7% growth is 398.5 TWh yr^{-1} (REMP, 2012). The potential clean energy from the food waste in this study is 31 TWh yr^{-1}, which would meet 7.8% of the 2020 projected power demand.~~ When considering the long-term projections (2021-2030) 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.

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 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).



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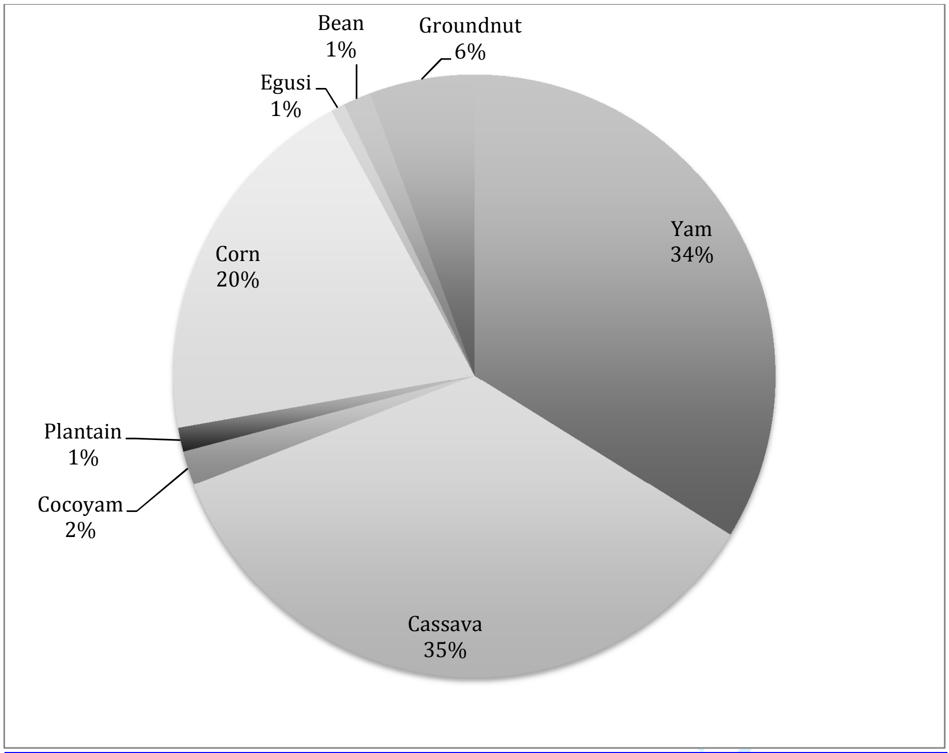

Figure 4. Potential Renewable Energy ~~Mix~~ contributions of common Nigerian food wastes ~~showing their various contributions~~.

~~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 cropss. 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 m^3 $tonne^{-1}$ on a Fresh Weight basis and (5.4 – 6.2) x 10^5 m^3 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 × 10^7 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:

Crude Fibre	*(C_rFd)*	*74.3%*
Crude Protein	*(C_rPd)*	*65.09%*
Crude Fat	*(OAHd)*	*67.51%*
NFE	*(NFEd)*	*69.97%*

Gas Yield Conversion Factors:

Carbohydrates	*(GYCf)*	*790 l kg^{-1}*
Proteins	*(GYPf)*	*700 l kg^{-1}*
Fat	*(GYOf)*	*1250 l kg^{-1}*

Methane content of Biogas:

Carbohydrates	*(MCf)*	*50%*
Proteins	*(MPf)*	*71%*
Fats	*(Mof)*	*68%*

Calculated Parameters

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

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

Baserga Equations:

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

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

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

And :

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

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

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

And :

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

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

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

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

And :

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

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

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

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

And :

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

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

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

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Calculations:

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

Annual Biogas Potential (m^3) = Annual Food Waste (tonnes) × BioMethane Potential of Food Waste (m^3/tonne)

Annual Methane Potential (m^3) = Annual Biogas Potential (m^3) × Methane Content (%)

Annual Energy Potential (MJ) = Annual Methane Potential (m^3) × Gross Calorific Value Methane (MJ/m^3)

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

Constants

Gross Calorific Value Methane = 38 MJ/m^3

1 MJ = 0.2778 kWh