



## ASSESSMENT OF AGRO-WASTE POTENTIALS FOR THE GENERATION OF ELECTRICAL ENERGY IN NORTHEAST NIGERIA

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### ABSTRACT

In this paper eight major Agricultural-wastes (agro-waste) (maize cob, groundnut shell, bean pod, wheat husk, rice husk, millet bran, sorghum bran and sugar cane bagasse) derived from widely grown crops in the northeast sub-region have been investigated for their energy resource potentials. The core research task is to estimate the aggregate crop residues from raw data collected from river basin authorities and ministries of agriculture and water resources as well as from structured surveys of major markets, large commercial farms and Agro-Allied Industries. This work relies on directed data analytics approach and has arrived at gross estimates of  $6.89 \times 10^4$  metric tons per annum as agro-wastes available for electricity production; corresponding to approximately 13.5% share of the total agro-wastes of the northeast sub-region. Further, samples of all agro-wastes were characterized via proximate analysis which yielded their respective lower heating values to be within the range of 12.52MJ/kg to 16.66MJ/kg. From end-use viewpoint, the estimated agro-wastes of the study area can generate electrical energy of 55.8GWh/annum for geographically scattered rural communities.

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### 1.0 Introduction

The humongous electricity supply gap in Nigeria will continue to remain thematic in the public domain and also cause indigenous energy resource exploitations in different Nigerian sub-regions so as to propel technically and economically viable distributed power generations. Undoubtedly, rapid increase in Nigerian population and urbanization has put enormous pressure on her national electric utility infrastructure which has not grown at commensurate rate over the years. Today, Nigeria's per capita energy consumption is still around 150kWh which is among the lowest in comity of developing and developed countries (World Bank, 2019). Although the electricity industry has been deregulated since 2005, the anticipated capital inflow to drive the rapid expansion of generation, transmission and distribution facilities has not materialized. But as part of efforts to diversify Nigeria's energy base, which currently relies heavily on conventional energy sources, the Federal Government has, as key component of her master energy plan, well-articulated distributed energy resources development for rapid socioeconomic development of the country (Renewable Energy Master Plan, 2005). Central to the master energy plan, is the development and utilization of the renewable energy sources for sustainable electricity supply to underserved consumers and unserved rural communities in Nigerian milieu without degrading the environment (Energy Commission of Nigeria (ECN, 2015). It is undeniable that the Nigerian economy is heavily dependent on the petroleum sector for the provision of over 80% of public

finance, despite instability in the international crude oil market. However, in spite of its significance to the national economy, the oil sector has not spurred real economic growth in the country. Despite the huge revenue that accrued from crude oil exportation, the infrastructural development has remained very low and in particular, electricity delivery to consumers nationwide is conservatively estimated to be 54.4%, according to (World Bank, 2019).

The North-East sub-region of Nigeria has numerous untapped energy resources that encompass majorly renewable energy sources and, to some limited extent, conventional energy sources. The missing nexus, however, is how best to deploy the viable energy resources to underpin sustainable economic growth of the sub-region. A well-researched energy resource database for Nigeria (Afolabi et al., 2021) and the entire north-east sub-region is not readily available and this is without prejudice to the existing research investigations on identified energy resource entities in some specific localities of north-east sub-region. The prime focus of this paper is to develop a viable road map for the utilization of the indigenous energy resources, in coordinated manner, for sustainable distributed power generation applications in the North-East sub-region. The specific task of this paper is to carry out comprehensive evaluation and characterization of different biomass resource potentials in the sub-region. The overriding goal concerns sustainable electricity productions for plethora of geographically dispersed rural communities, across the entire northeast sub-region that currently lack electricity delivery from the national grid.

Biomass is organic material made from plants and animals. Plants absorb the sun's energy in a process called photosynthesis. The chemical energy in plants gets passed on to animals and people that eat them. Biomass is a renewable energy source because people always grow more trees and crops, and waste will always exist. The overall biomass resources can be broadly categorized into two parts based on its availability in the natural form woody and non woody biomass (Aruya et al. 2016; Anne, 2013 and Simonyan & Fasina, 2013) all defined agricultural residues as organic materials produced as byproduct during the harvesting and processing of agricultural crops. Lack of electricity infrastructures in rural areas of most African countries remain the main barrier to their socio-economic development (Aderoju et al., 2017). One of the principal causes is the geographical dispersion of the population and the large locational distances of rural communities from the existing electricity network outlay. Another key reason is the financial strengths of the various African governments which do not enable them invest heavily in electrification of rural areas (Anicet, 2012).

There have been several studies on the aforementioned issues in Nigeria and other developing countries to look at cost effective off mini-grid electricity supply solutions. Several techniques and approaches have been developed to evaluate and characterize different energy resource scenarios with attention focused for the time being on biomass. Dan (2008) reviewed the current state and trends in using fuel, solid wastes generated in pulp and paper mills. Rishi (2013) worked on the estimation of power generation potential of agriculturally based biomass species. The researcher worked on four selected agricultural residues comprising maize, coconut, paddy and *Cajanus cajan* and land cultivation requirements to enable sustainable electricity generation. The result further showed that approximately 717 hectares, 1123 hectares, 1511 hectares and 4319 hectares of land are required to generate 20MWh/day of electricity from coconut, maize, and paddy and *Cajanus cajan* residues respectively. Katherine et al., (2016), worked on Assessment of the Energy Potential of Agricultural Residues in Non-Interconnected Zones of Colombia: Case Study of Chocó and Putumayo. The energy potential of agricultural residues in two departments of ZNI in Colombia was estimated. (Awulu et al., 2018) worked on the comparative Analysis of Calorific Values of Selected Agricultural Wastes. This author worked on determining the calorific values of Corn cob, Rice husk and Sawdust agricultural wastes materials. Standard method of calorific value determination involving the use of Bomb Calorimeter was adopted. From the investigation,

the calorific value of Rice husk, Sawdust and Corn cob are 2938.86 kcal/kg, 3155.30 Kcal/kg and 3227.78 kcal/kg respectively.

In order to exploit solid biomass species for electricity generation, it is pertinent to determine their properties that include calorific value, volatile matters, moisture content etc. Wood and agricultural residues are burnt as a fuel for cogeneration of steam and electricity in the industrial sector (Sartolli et al, 2023., Vaibhav and Avin, 2014). Biomass can also be converted to a liquid form for use as a transportation fuel, and research is being conducted on the production of fuels and chemicals from biomass. In the electricity sector, biomass is used for power generation (Rishi, 2015). Sources include forest residues, rice husk, wood chips, sorghum, sugarcane, etc. As an energy resource, biomass may be used as solid fuel, or converted via a variety of technologies to liquid or gaseous forms for the generation of electric power, heat or fuel for motive power (Navneer 2014.; ) reported that not all the Waste Agriculture Biomass (WAB) have same thermal values. The calorific values of some selected biomass samples, on dry basis, extracted from archives of Bimtech Birla Institute of Management Technology vary between 3000 and 4700 Kcal/Kg. This paper also presents experimental work, using proximate analysis to determine calorific values of different agricultural biomass species indigenous to northeast sub-region of Nigeria.

## **2. Materials and Method**

### **2.1 Data Collection**

This section presents comprehensive documentation of the materials and methods deployed to realize the aim and objectives of this paper. The data collection procedures are anchored firstly on structured survey-based studies to enable collection of credible raw data on annually generated agro-wastes by agro-industries and large farms in the northeast sub-region of Nigeria; Different methodologies are developed: to estimate, firstly, the aggregate annual agro-wastes and their respective calorific values for the entire northeast sub-region; secondly determine optimum allocation of agro-wastes for electricity generation. The integral components of materials and methods are set forth in the subsequent sections that follow in sequel.

#### **2.1.1 Data collection sources for agro-wastes in northeast sub-region**

All state ministries of agriculture, large agro-processing industries, large markets, river basin authorities etc., constitute the sources to provide credible data via suitably structured survey questionnaires/oral interviews. The data sought are as follows:

1. All or some available data from all state ministries of agriculture in northeast on cultivated arable land area in hectares of each state; dominant crops grown annually specific to each state; expected average yield (metric tons/hectare) per each crop type grown and gross estimate of productions (metric tons per annum) per each crop for each state.
2. Additional data sourced from agro-industries/processing points in all northeastern states to estimate specific agro-wastes produced annually;
3. All processed agro-crops of each state sold at large markets, for all year-round market days, and transported to other states or as obtained from the respective market logbooks where available.

### **2.2 Experimental Procedure**

This section presents the core methodologies developed for the actualizations of our research objectives. More precisely, the following constitute the core methodologies developed herein.

- a) Design of structured survey questionnaires to fairly accurately facilitate estimations of agro-wastes generated annually in each state of northeast sub-region of Nigeria.

- b) Flowchart for Data Collection Procedure on Agro-wastes presented in (Figure 1).
- c) Experimental setup to carryout proximate analysis on samples of major agro-wastes for each state of northeast sub-region of Nigeria;
- d) Problem formulation for equitable utilization of agro-wastes in northeast Nigeria; and

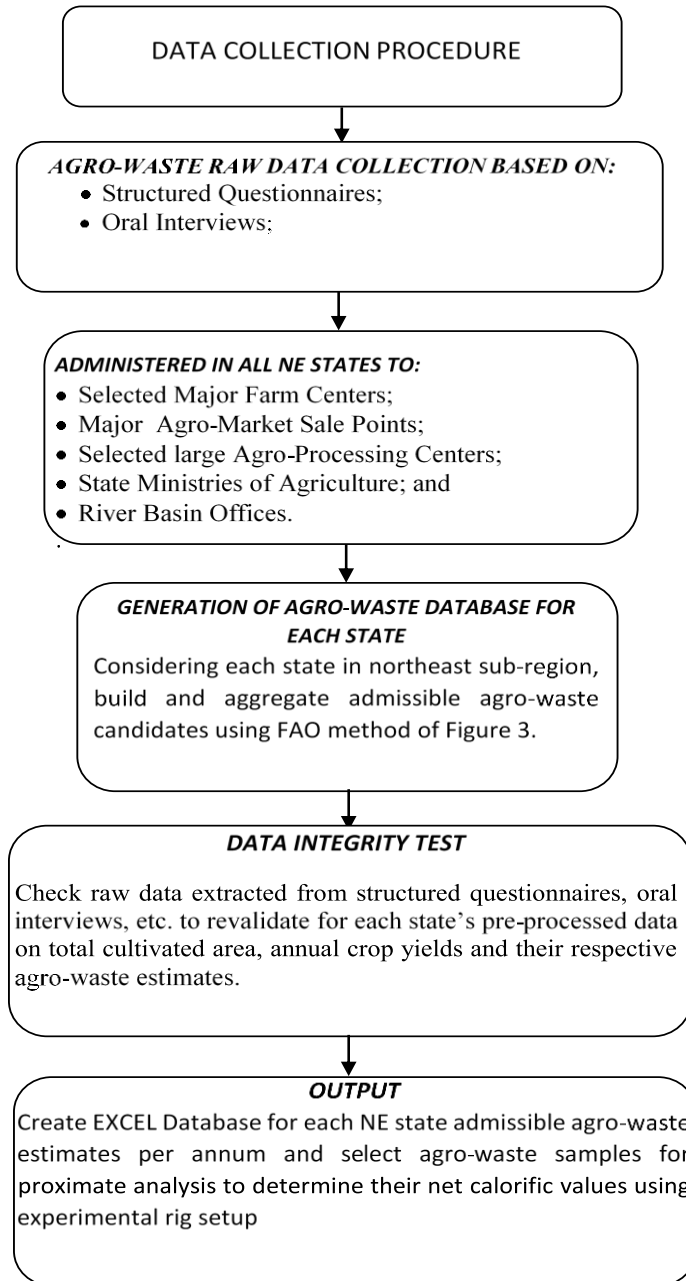
### **2.2.1 Design of structured survey questionnaire for agro-waste estimation in study area**

The observed lack of credible data on agro-wastes, in the public domain, for the entire northeast, has motivated the design of structured survey questionnaires upon which we anchored the estimations of the agro-wastes or crop residues for each state in the study area. It is, of course, unarguable that realistic estimates of major agro-wastes are pertinent to drive sustainable energy stock inputs for modularized power generation schemes. Consequently, well-structured survey questionnaires constitute least cost terrestrial-based option to gather reliable and trusted data within the study area. Specifically, the design of the structured survey questionnaires seeks vital data and information for each state in northeastern Nigeria that include the following amongst others:

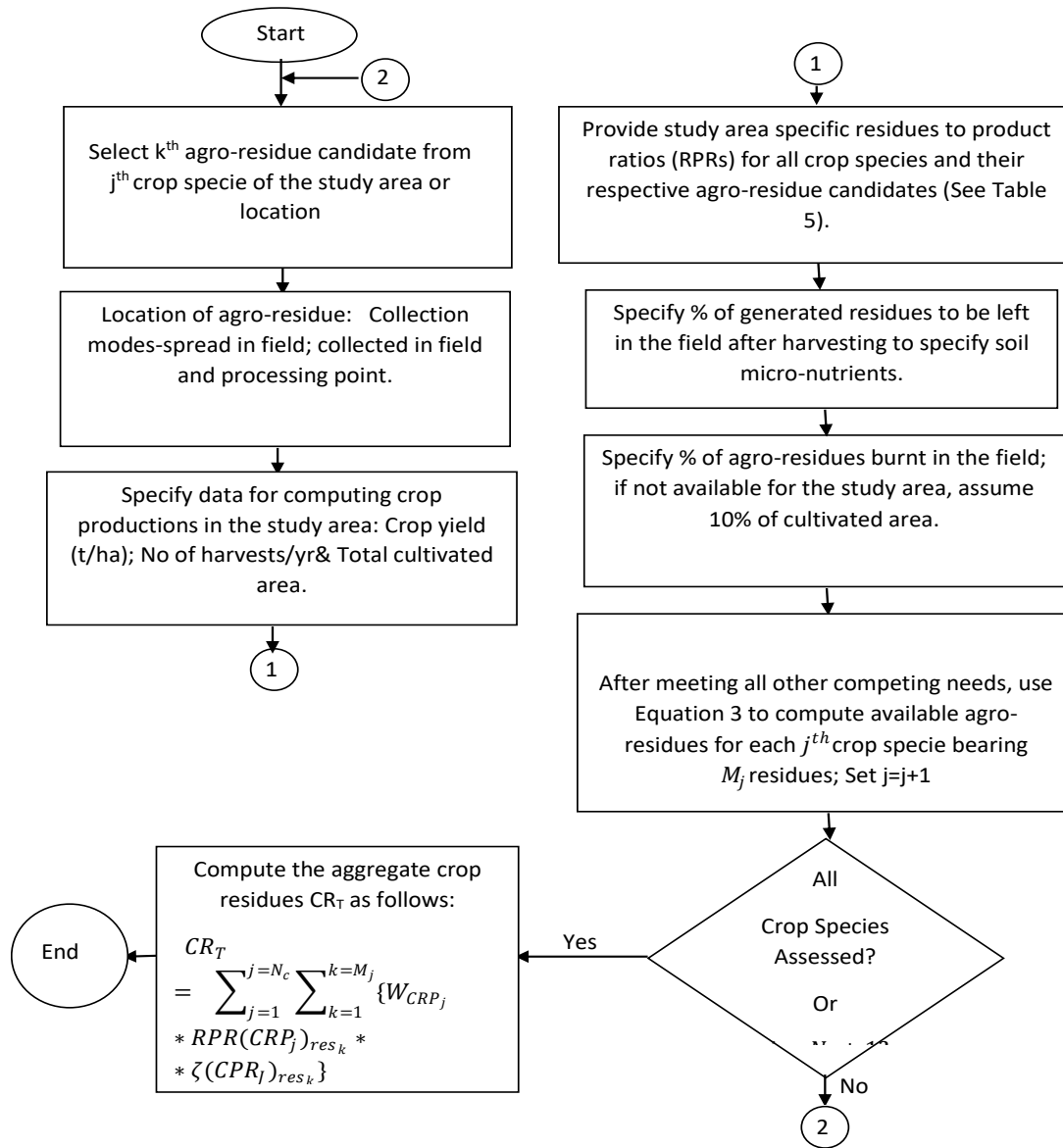
1. Arable and cultivated land in hectares (ha) or square kilometers (km<sup>2</sup>) per annum and distributions among the major crops grown including large- and small-scale farmers;
2. Major crops grown and number of times per year stating if rain-fed or irrigation-fed or both and yield per ha for each crop type.
3. Large farms (in hectares) owned by agro-allied industries, private individuals specifying crops cultivated and if rain-fed or irrigation fed and to indicate number of harvests per annum achievable.
4. Large markets that specialize in the sales of preprocessed agricultural crops to access their sales records and determine whether for local retails or out of state transportation each year.

We then relied on suitably structured survey questionnaires administered to all the state ministries of agriculture, all river basin authority offices, and major markets in northeast sub-region of Nigeria that returned reliable responses.

(Figure 1) depicts the algorithmic framework of the final structured survey experimentations carried out culminating in pragmatic estimations of agro-wastes for each state in northeast sub-region for only dominant crops grown. The underlying computational procedures for the agricultural residues in the study area are set forth in sequel which essentially relies on FAO approach of (Figure 2).



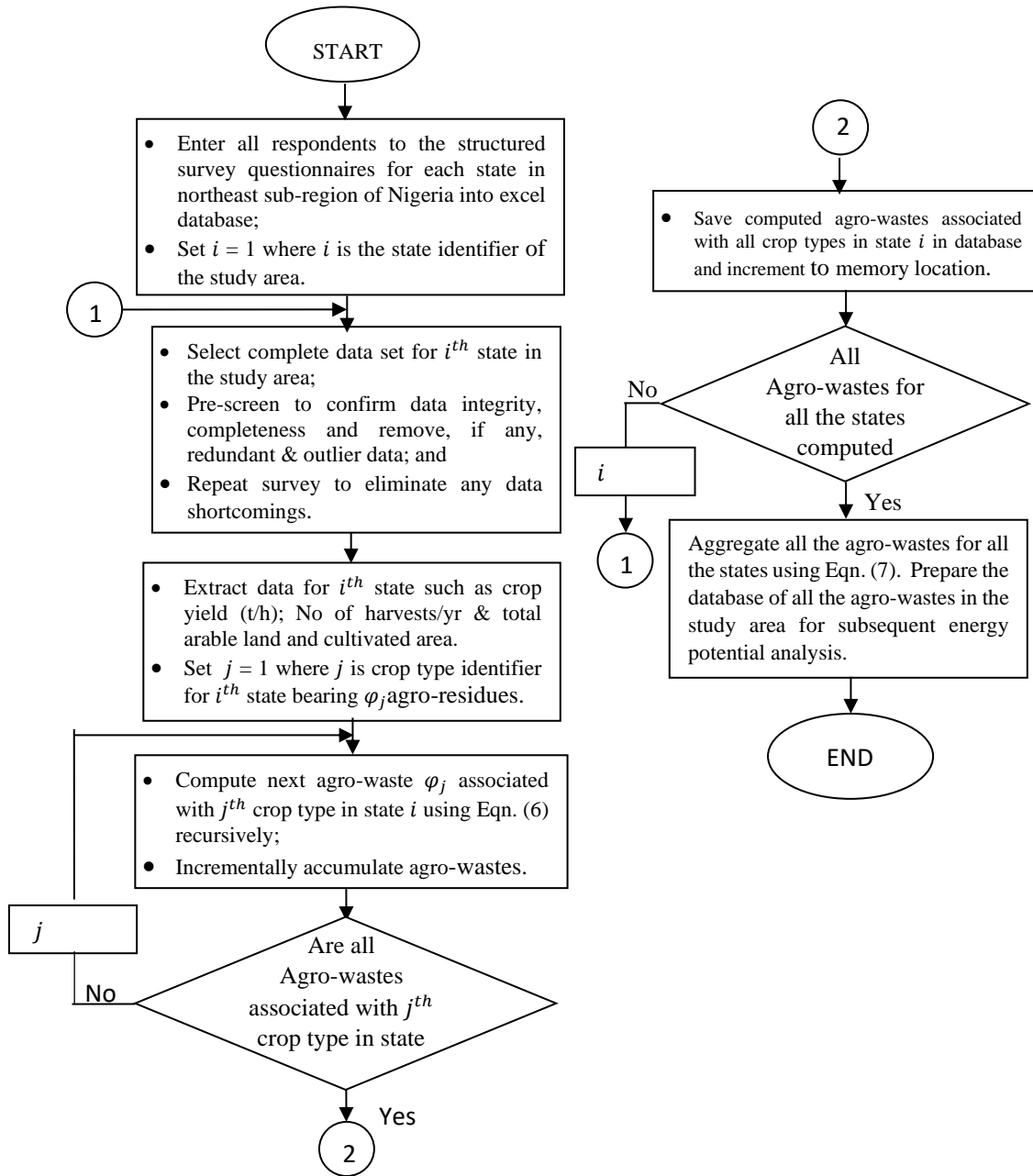
**Figure 1.** Flowchart for Data Collection Procedure on Agro-wastes,



**Figure 2:** Flowchart for Estimating Agricultural Residues Source (FAO, 2014).

### 2.2.2 Experimental setup for determination of agro-waste energy content

(Figure 3) depicts the functional block diagram of experimental setups that enabled the determination of heating values or calorific values of the dominant agro-wastes considered in all the states of northeastern Nigeria. The aforementioned experimental setups cannot determine the calorific value directly as done by oxygen bomb calorimeter; but instead determine explanatory variables such as Moisture Content(*MC*), Ash Content(*AC*), and Volatile Matter(*VM*) from which the corresponding calorific value is estimated from empirical relationships. For the sake of completeness, (Figure 4) shows the experimental setup for the determination of crude protein of the various agro-wastes to establish their nutritional values as animal feeds.



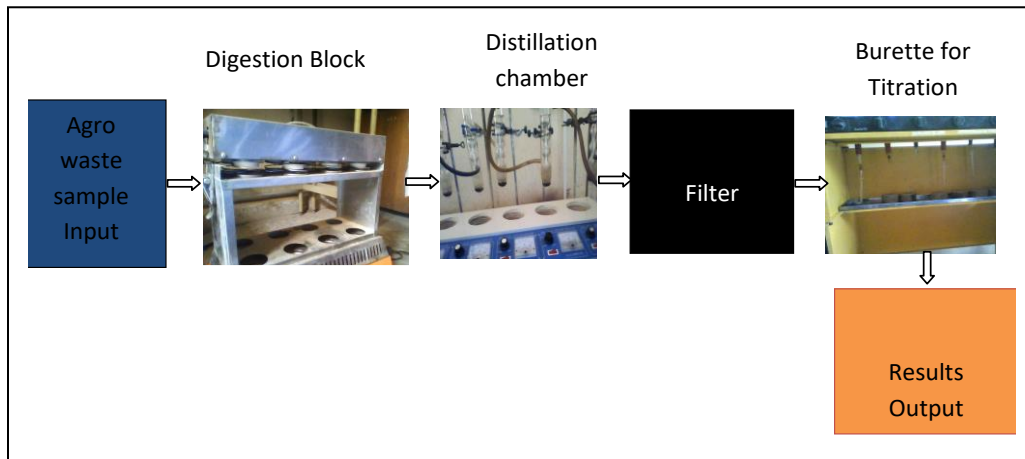
**Figure 3:** Developed Flowchart for the computation of Agro-wastes in the Study Area

### 2.2.2.1 Proximate Analysis procedure for calorific value determination of agro-wastes

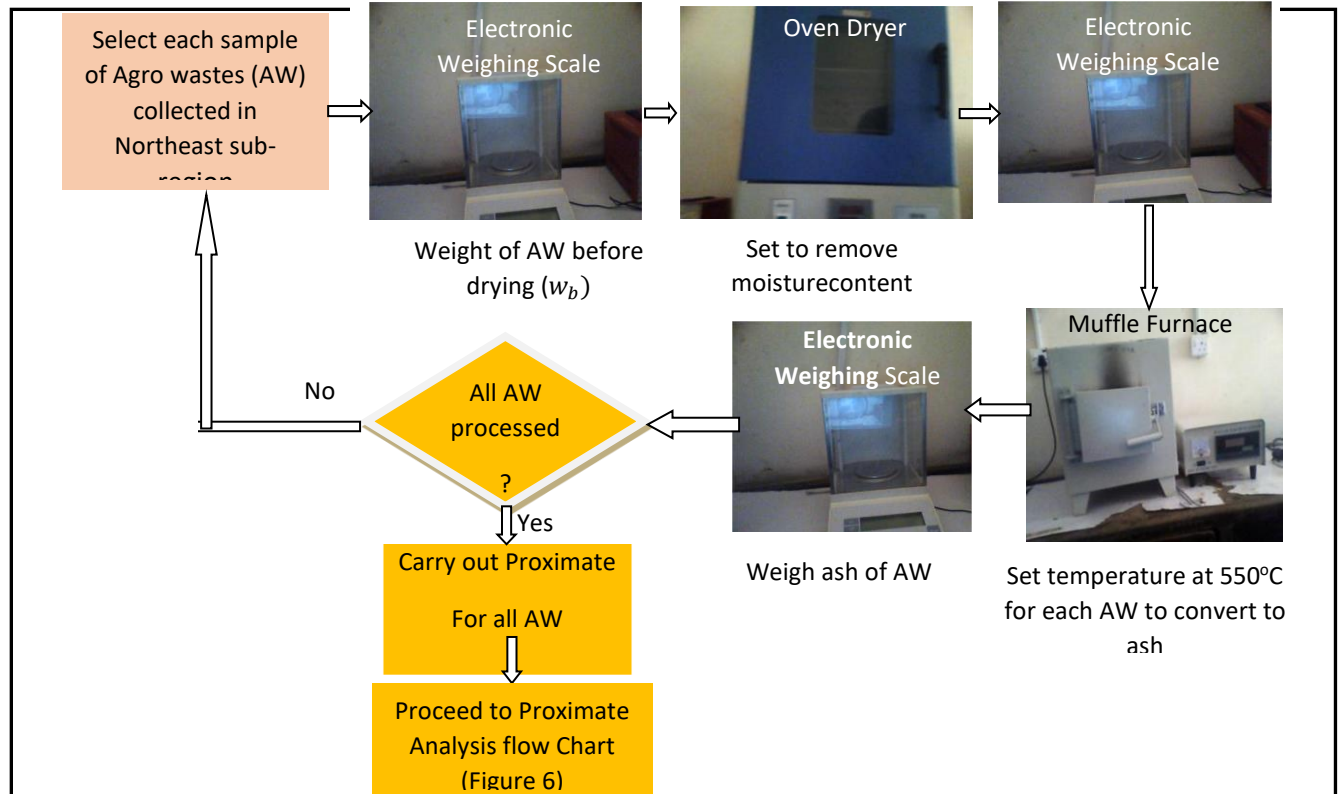
The implementations of proximate analysis on agro-wastes are indispensable because they provide their energy contents to be harnessed for distributed end-use electricity productions. Indeed, proximate analysis of agricultural biomass residues for selected study areas in different countries have appeared in several publications but similar studies have not been carried out in respect of dominant crop residues in the study area of interest. The research goal is, therefore,

to evolve standardized templates of calorific values for the dominant agro-wastes in the northeast sub-region of Nigeria.

The proposed methodology for the implementation of proximate analysis should perform the same function as Oxygen Bomb Calorimeter. (Figure 5) depicts the overall flow chart for the proximate analysis experimental and computational framework. The salient steps of proximate analysis are further highlighted in what follows. The algorithmic flowchart is presented in (Figure 6).

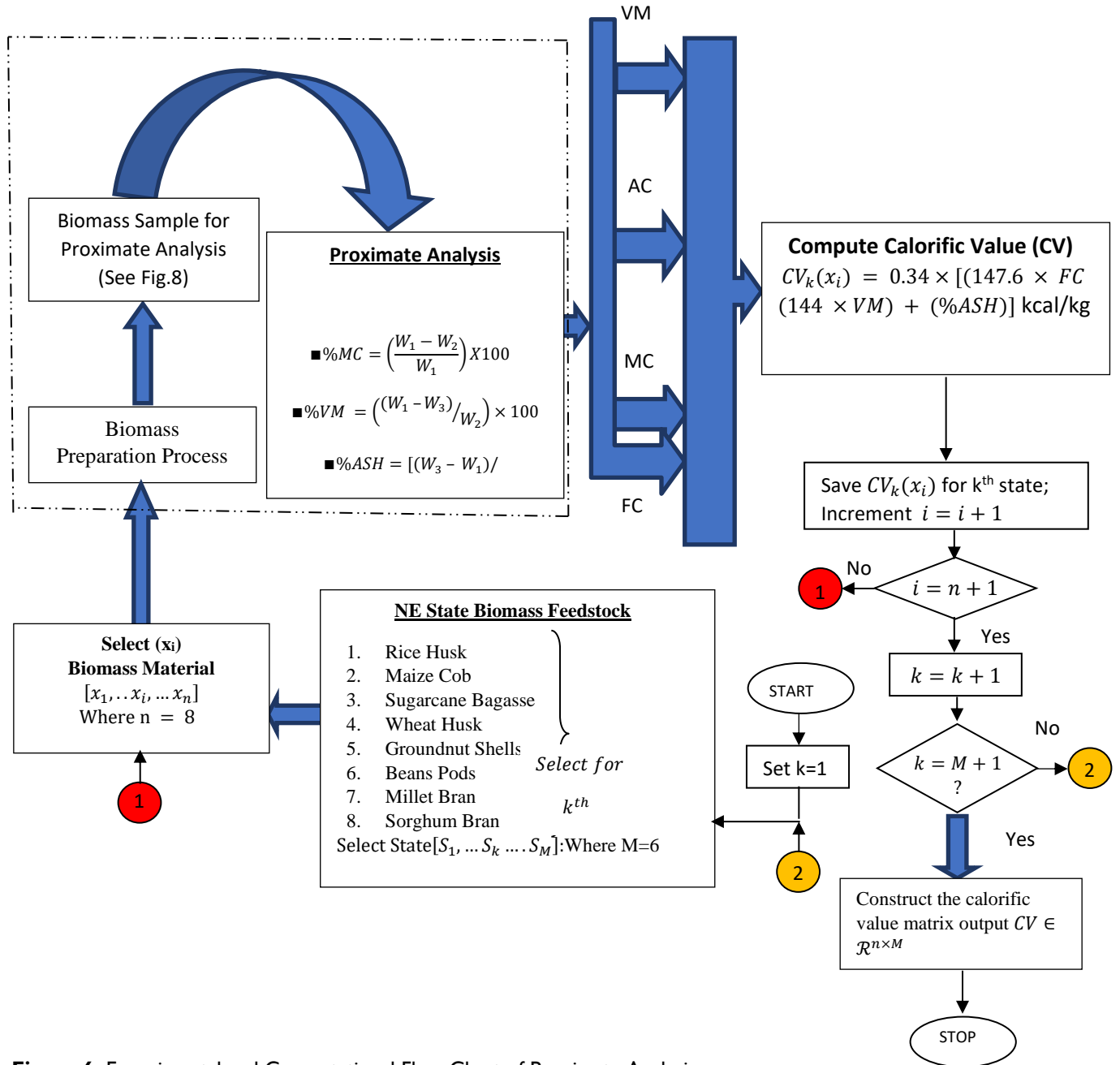


**Figure 4:** Experimental Setup for the Determination of Agro-Waste Crude Protein



**Figure 5:** Experimental Setup for Agro- Waste Proximate Analysis





**Figure 6:** Experimental and Computational Flow Chart of Proximate Analysis

**Step1 (Sample preparation):** Eight different biomass samples were collected from the major processing points of the six states of the sub-region and experiment was performed separately on each of the sample. One gram of powdered sample of each were taken forth analysis of ash content, moisture content, volatile matter and fixed carbon content.

**Step2 (Moisture determination MC):** Add one gram of air-dried powdered sample to a crucible disc and keep in the air oven maintained at the temperature  $105^{\circ}\text{C}$ . The sample is kept at this temperature for 30 min and then taken out from the furnace and cooled off in a desiccator. Weight loss was recorded using an electronic balance. The percentage loss in weight is the percentage moisture content (%MC) in the sample as given in Eqn. (1).

$$\%MC = \left( \frac{W_1 - W_2}{W_1} \right) \times 100 \quad (1)$$

Where:

$W_1$ : is the weight of sample plus crucible before drying and  $W_2$ : is the weight of sample after drying in the oven dryer.

**Step2 (Volatile matter determination VM):** Add one gram of air-dried powdered sample in a volatile matter crucible and place in muffle furnace maintained at temperature of 650°C. The sample should be maintained at this temperature for 7 minutes and then taken out, air cooled and then weighed ( $W_3$ ). Weight loss in the sample is recorded again by using an electronic balance having a sensitivity of 0.001 gram. The percentage loss in weight – moisture present in the sample over the dried weight yields the volatile matter content in the sample Eqn. (2).

$$\%VM = \left( \frac{W_2 - W_3}{W_2} \right) \times 100 \quad (2)$$

**Step3 (Ash content determination ASH):** Add one gram of air-dried powdered sample in a shallow silica disc and kept in the muffle furnace maintained at the temperature of 550°C. The sample is kept in the furnace to achieve complete combustion. Weight of ash formed is then measured and the percentage ash content in the sample determined by Eqn. (3).

$$\%ASH = \left( \frac{W_3 - W_1}{W_2 - W_1} \right) \times 100 \quad (3)$$

Where:

$W_1$  = Weight of empty crucible;  $W_2$  = Weight of crucible + sample and  $W_3$  = Weight of crucible + ash.

**Step4 (Fixed carbon, FC, determination):** The fixed carbon content in each agro-waste sample is determined using the following formula:

$$\%FC = 100\% - Wt\%(Moisture + Volatile Matter + Ash) \quad (4)$$

**Step5 (Calorific value/specific heat of combustion CV or LHV):** The specific heat of combustion or calorific value (CV) in kcal/kg of any residues is then computed using the following empirical formula:

$$CV = 0.35\{(147.6 * \%FC) + 144 * \%VM + (\%ASH)\} \text{ (kcal/kg)} \quad (5)$$

It is noteworthy that in order to determine moisture content of the agro-waste sample, it must be heated in air oven at temperature of 105°C for about 30min. Secondly, the determination of ash content required that the agro-waste under consideration must undergo complete combustion in the muffle furnace maintained at 550°C; whilst the determination of volatile matter require that the agro-waste sample be heated in the furnace at higher temperature of 650°C. It is pertinent to re-iterate again that lack of functional bomb calorimeter apparatus, engendered the alternative experimental rig to actualize one of our cardinal research goals of determining

calorific values for different species of agro-wastes from dominant crops cultivated in the states in the northeast sub-region.

### 2.3 Derivation of Energy Potential of Agro-wastes

The ultimate goal of this research is to determine energy potential of agro-wastes generated in the different states of the northeast and subsequently characterize their technical and economic viability for sustainable electrical energy productions. Having developed pragmatic framework for the estimation of agro-wastes in the study area and determinations of their respective calorific values via proximate analysis, we can now assess the energy potential derivable from them. Consider again an arbitrary study area split into N states with each state having K dominant crop types such that  $j^{th}$  crop type that can generate  $M_j$  agro-wastes or crop residues. Starting from Eqn. (1), the theoretical energy potential of  $i^{th}$  state ( $\mathbb{E}_i^{TEP}$ ) and entire study area ( $\mathbb{E}_{SA}^{TEP}$ ) can be expressed as given in Eqn. (6) and Eqn. (7), respectively:

$$\mathbb{E}_i^{TEP} = \sum_{j=1}^K \left( \sum_{res_{\varphi}=1}^{M_j} \left( W_{CRP_j} \times (\zeta_j \times A_{ci}) \times (RPR_j)_{res_{\varphi}} \times CV(CRP_j)_{res_{\varphi}} \right) \right) \times 10^{-3} (MWh_T) \quad (6)$$

$$\mathbb{E}_{SA}^{TEP} = \sum_{i=1}^N \mathbb{E}_i^{TEP} \quad (7)$$

Where all the other variables used in Eqn. 7 have been previously defined.

The possibility of utilizing all the admissible crop residues for electricity generation in the study area is unattainable because of equally critical competing needs such as animal feeds, farmer organic manure, etc. It is therefore imperative to share gross agro-wastes for the study area amongst all the potential areas. Consequently, optimally determined sharing allocation weighting fractions defined as  $\alpha(CRP_j)_{res_{\varphi}} < 1$ ; {for every  $j \in [1, 2 \dots K]$ ;  $res_{\varphi} = [1, 2, \dots, k, \dots, M_j]$ } are introduced into Eqn. (6) to yield the modified equations, for technical energy potentials for  $i^{th}$  state ( $\mathbb{E}_i^{tech}$ ) and the study area ( $\mathbb{E}_{SA}^{tech}$ ) as Eqn. (8) and Eqn. (9), respectively.

$$\mathbb{E}_i^{tech} = \sum_{j=1}^K \left( \sum_{res_{\varphi}=1}^{M_j} \left( W_{CRP_j} \times (\zeta_j \times A_{ci}) \times (RPR_j)_{res_{\varphi}} \times CV(CRP_j)_{res_{\varphi}} \times \alpha(CRP_j)_{res_{\varphi}} \right) \right) \quad (8)$$

$$\mathbb{E}_{SA}^{tech} = \sum_{i=1}^N \mathbb{E}_i^{tech} \times 10^{-3} MWh yr^{-1} \quad (9)$$

Note that  $\mathbb{E}_i^{tech} < \mathbb{E}_i^{TEP}$  and  $\mathbb{E}_{SA}^{tech} < \mathbb{E}_{SA}^{TEP}$  due to inclusions of sharing allocation fractions. The foregoing is formulated in the next subsection as resource allocation problem.

#### 2.3.1 Resource allocation problem formulation for agro-waste utilization

The utilization of agro-wastes as feedstock for electricity generation chain process in the northeast sub-region of Nigeria is formulated as essentially resource allocation problem. This is because there is other competing utilization of agro-wastes such as animal feeds, building and

cooking requirements by humans, farm manures and other engineering applications such as soil binders, cement additives etc.

### 2.3.1.1 Problem formulation

Assume  $m$  admissible agro-wastes generated in metric tons/annum are denoted as  $\{W_1, W_2, \dots, W_i, \dots, W_m\}$  and their corresponding calorific values in MJ/Ton are denoted as  $\{cv_1, cv_2, \dots, cv_i, \dots, cv_m\}$ . Let  $\{X_v: v = 1, 2, \dots, n\} \in R^n$ ; represent the agro-waste allocations per annum to  $n$  end users. Let  $X_k^{(e)}$  represent the total contributions from all the admissible agro-wastes as feedstock for electricity production given by Eqn. (10)

$$X_k^{(e)} = \sum_{i=1}^m \alpha_i^{(k)} \times W_i \quad (10)$$

Where  $\alpha_i^{(k)}$  is the fraction of  $i^{th}$  agro-waste  $\forall i \in \{1, m\}$  that is allocated to  $k^{th}$  electricity end user where  $k \in \{1, n\}$ .

The mathematical formulation of the agro-waste allocation problem for electricity production can be cast as Eqn. (11)

$$1) \text{ Cost Function: } Max E_T(X_k^{(e)}) = \sum_{i=1}^m (\alpha_i^{(k)} \times W_i \times CV_i) \quad (11)$$

Subject to the following equality and inequality constraints:

2) Equality Constraints form agro-wastes shared amongst  $n$  end-users using optimally specified fractions  $\alpha_j^{(k)}$  for  $k = 1, 2, \dots, n$  and each  $j = 1, 2, \dots, m$  as stated in Eqn. (12).

$$\left. \begin{aligned} X_1 &= \alpha_1^{(1)}W_1 + \alpha_2^{(1)}W_2 \dots + \alpha_j^{(1)}W_j \dots + \alpha_{m-1}^{(1)}W_{m-1} + \alpha_m^{(1)}W_m \\ X_2 &= \alpha_1^{(2)}W_1 + \alpha_2^{(2)}W_2 \dots + \alpha_j^{(2)}W_j \dots + \alpha_{m-1}^{(2)}W_{m-1} + \alpha_m^{(2)}W_m \\ X_k^{(e)} &= \alpha_1^{(k)}W_1 + \alpha_2^{(k)}W_2 \dots + \alpha_j^{(k)}W_j \dots + \alpha_{m-1}^{(k)}W_{m-1} + \alpha_m^{(k)}W_m \\ X_n &= \alpha_1^{(n-1)}W_1 + \alpha_2^{(n-1)}W_2 \dots + \alpha_j^{(n-1)}W_j \dots + \alpha_m^{(n-1)}W_m \\ X_n &= \alpha_1^{(n)}W_1 + \alpha_2^{(n)}W_2 \dots + \alpha_j^{(n)}W_j \dots + \alpha_{m-1}^{(n)}W_{m-1} + \alpha_m^{(n)}W_m \end{aligned} \right\} \quad (12)$$

The total agro-wastes ( $W_T$ ) is then given by

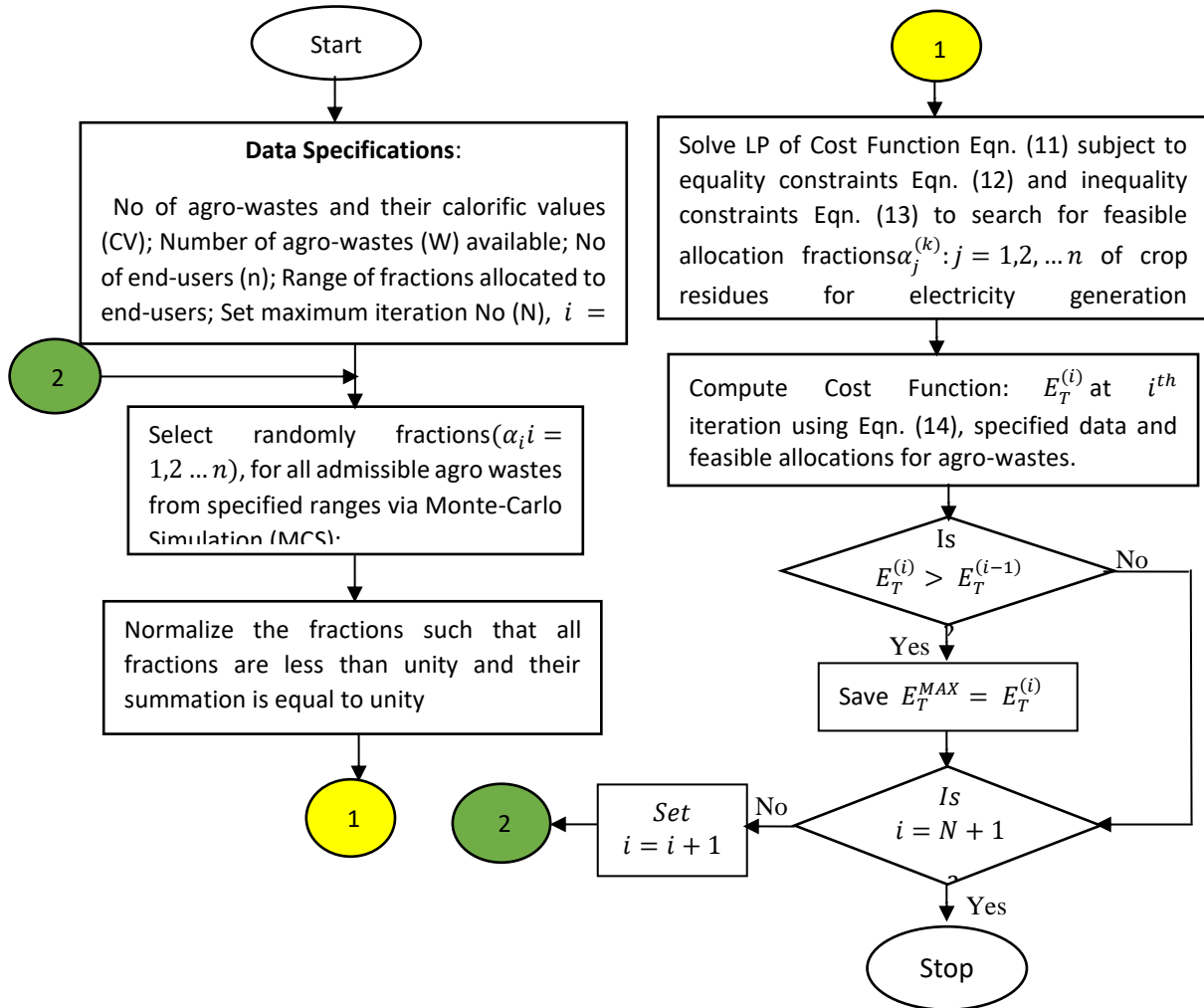
$$W_T = W_1 + W_2 \dots + W_j + \dots + W_{m-1} + W_m \rightarrow \sum_{i=1}^m W_i \quad (13)$$

3) Inequality Constraints are summarized in Eqn. (14).

$$\left. \begin{aligned} \alpha_{min_j}^{(k)} \leq \alpha_j^{(k)} \leq \alpha_{max_j}^{(k)} \quad j = 1, 2, \dots, m \quad \forall k \in \{1, n\} \\ 0 < \sum_{i=1}^n X_i \leq W_T \end{aligned} \right\} \quad (14)$$

$$0 < \sum_{k=1}^n \alpha_j^{(k)} \leq 1 \quad \forall j = 1, 2, \dots, m$$

The foregoing generalized agro-waste resource allocation formulation is essentially a linear programming (LP) problem. (Figure 7) shows the flow chart for obtaining the Pareto optimal solution to the LP problem using the Monte- Carlo simulation and greedy approach.



**Figure 7:** Flowchart for LP Based Agro Waste Resource Allocation

### 3. Results and Discussion

#### 3.1 Results of Major Crops Produced by Each State in Northeast Sub-region

Referring to Table 1, it is seen that Borno State returned the highest productions of Rice and Wheat whilst Adamawa State has the highest production of Sugar Cane in the northeast sub-region. By extension, they also produced corresponding agro-wastes per annum from the crop types mentioned and the benchmark RPR utilized as presented in Table 2. Note that Borno state returned as the highest producer of rice with total cultivated area of 45,000 hectares of land with an estimation of  $22.5 \times 10^6$  metric tons per annum at minimum production rate of 10 bags of 50kg per hectare of paddy rice and also a gross estimate of  $15.75 \times 10^6$  metric tons of wheat at a

minimum production rate of 7 bags of 50kg per hectare per annum. Further detailed analysis carried out with respect to other crop types and for other states as depicted in the pie charts and column bars of Figures 8-10.

**Table 1:** Estimates of Total Cultivated Areas in Hectares for Major Crops Grown in NE States

S/No	Crop Type	CULTIVATED AREAS IN NE SUBREGION STATES (x 10 <sup>3</sup> HECTARES)							Total Production (x10 <sup>6</sup> MT)
		Adamawa	Bauchi	Borno	Gombe	Taraba	Yobe	NE	
1	Sugar Cane	44.00	0.48	0.23	0.45	2.5	0.32	47.98	19.4
2	Maize	38.92	11.49	21.60	6.45	13.50	1.00	92.96	92.96
3	Millet	5.40	4.03	12.10	8.00	2.10	11.20	42.83	14.99
4	Beans	18.20	5.61	9.45	5.90	12.60	5.40	57.16	17.15
5	Sorghum	5.01	1.00	11.25	5.05	9.80	2.00	34.11	255.77
6	Groundnut	3.70	2.10	7.02	1.80	4.14	3.70	22.46	5.61
7	Wheat	0.35	8.00	45.00	0.12	0.41	4.20	58.08	231.84
8	Rice	20.02	12.30	61.20	2.00	4.60	4.20	104.32	365.12
<b>Total</b>		135.60	45.01	167.85	29.77	49.65	32.02	459.90	1002.84

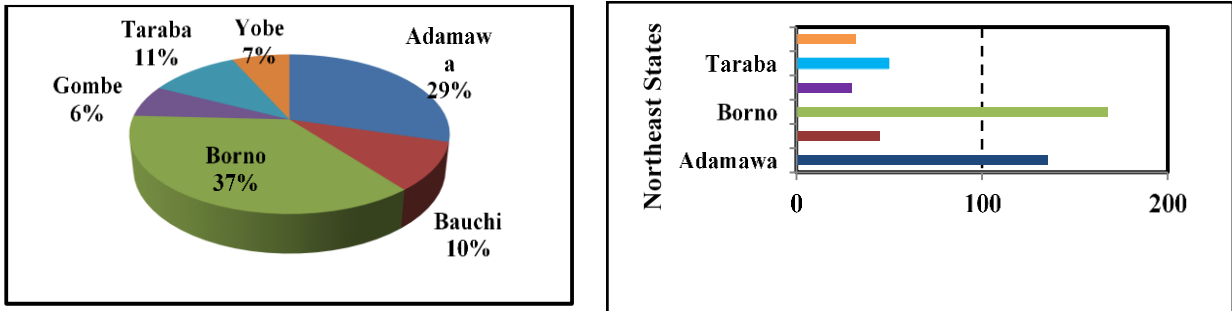
**Table 2:** Major Crops Produced by Each State in Northeast Sub-region

S/No	State	Crop Type Production (MT x10 <sup>3</sup> )							
		Maize	Rice	Beans	Millet	Sorghum	Sugar Cane	Wheat	Ground Nut
1	Adamawa	214	105	127	58	132	998	18	45
2	Bauchi	55	262	46	53	89	4	147	62
3	Borno	100	460	205	140	95	5	230	101
4	Gombe	152	22	160	72	129	10	27	103
5	Taraba	289	55	380	131	212	45	33	95
6	Yobe	166	265	278	74	111	11	127	198
<b>Total</b>		1583	1511	2014	805	1220	1139	769	604

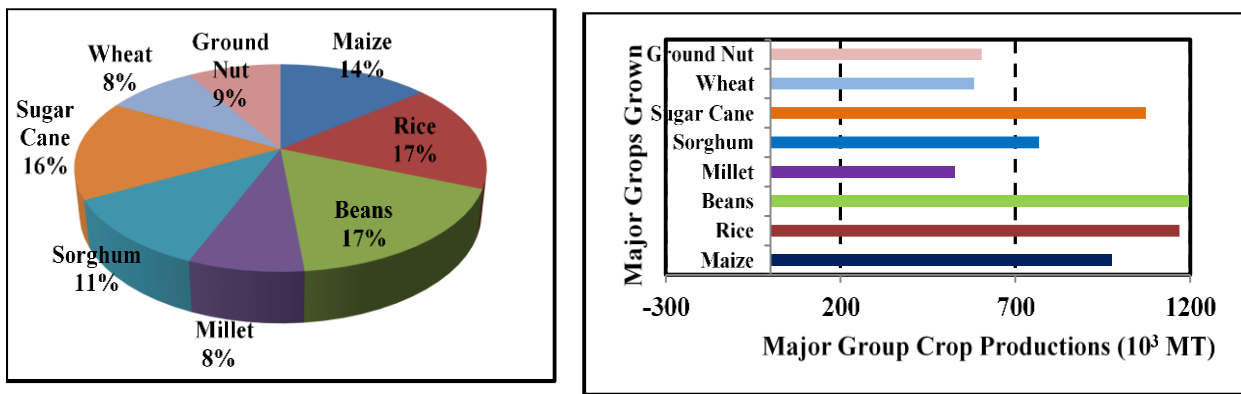
We relied on the procedure outlined in the flowchart of (Figure 7) as it concerned agro waste estimation anchored on data collected from river basin authorities within the northeast sub-region. With the raw data from various sources aggregated to remove redundancies, repetitions, etc yielded preprocessed data, from which credible results emanated. Relying on directed data aggregation algorithm applied to data collected spanning for over five years, we have estimated and recorded respectively, revealing benchmark values for cultivated areas annually for major crops, major crops produced annually per each state and cumulative annual crop residues generated in all the northeastern states of Nigeria.

The agro-wastes generated in the entire northeastern states as analyzed graphically as displayed in (Figures 8-10) clearly revealed the humongous quantities available in the northeast sub-region of Nigeria. The estimated  $2 \times 10^8$  metric tons of agro-wastes generated in the northeast sub-region, in this work which originated from structured survey analyses and databank of well-established agricultural entities in NE, are found to be more reliable and representative than extrapolations from existing generic data published by Energy Commission of Nigeria (ECN) and published work (Simonyan and Fasina, 2013). It can be argued, and rightly so, that the data generated might be patently conservative due to exclusion of small-scale holding farmers and more importantly insecurity that threatens farming activities in the sub-region. We have,

therefore, adopted error bars randomly selected from the band  $\pm$  (10%-25%) depending on the location in this study area to capture the uncertainties inherent in the agro-waste estimation effort. It has been conclusively established that agro-wastes are available, in abundance, in the northeast sub-region to prosecute sustainable distributed electricity productions.



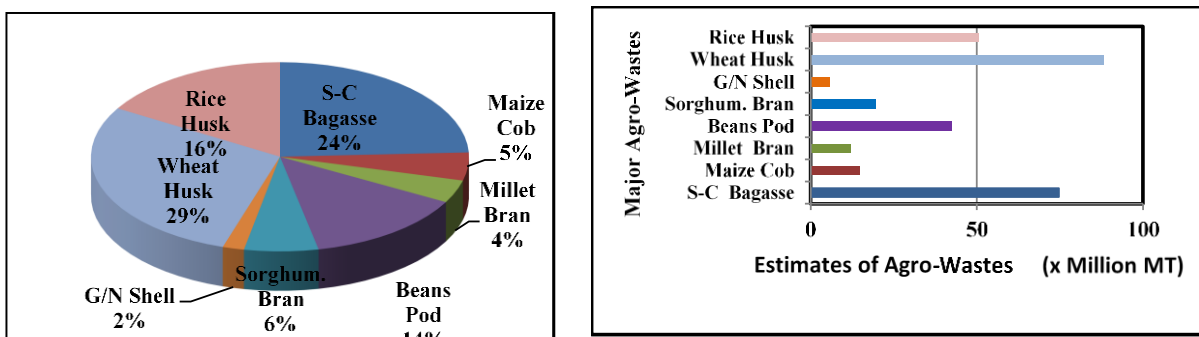
**Figure 8:** Pie and Bar Representations of Cultivated Lands in NE States for Major Crops Grown



(a) Pie Chart Representation in %

(b) Bar Chart Representation in metric tonnes

**Figure 9:** Pie and Bar Representations of Major Crops Productions in NE States



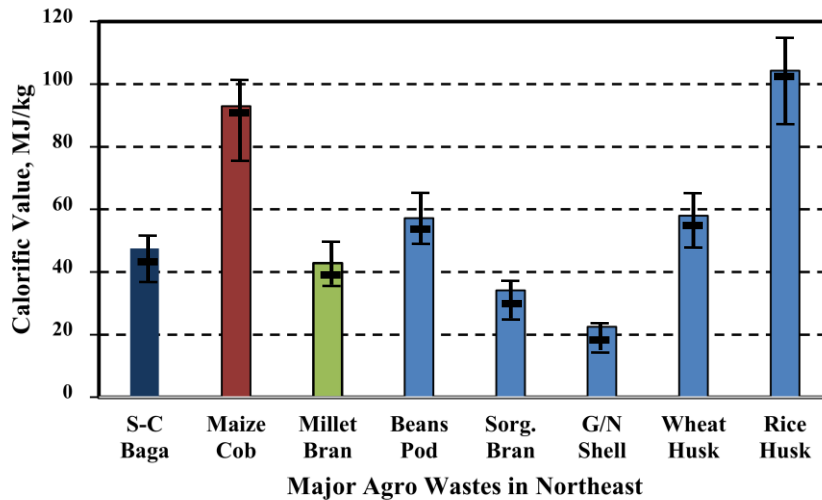
(a) Pie Chart Representation in %

(b) Bar Chart Representation in metric tonnes

**Figure 10:** Pie and Bar Representations of Agro-Wastes from Major Crops Grown in NE States

### 3.2 Results of proximate analysis of major agro-waste samples in northeast states

This subsection presents results of proximate analysis carried out on the biomass samples (Agro waste or agricultural residues) for each state in the northeastern sub-region. This is in accordance with the experimental setups of (Figures 4 and 5) with algorithmic flowchart of (Figure 6) applied to compute the calorific value for all the admissible agro-wastes from each state in northeast sub-region. The proximate analysis results for each state are presented in Table 2. Table 2 depicts the benchmark values of LHV for all the admissible agro-wastes with their respective error bars also indicated.

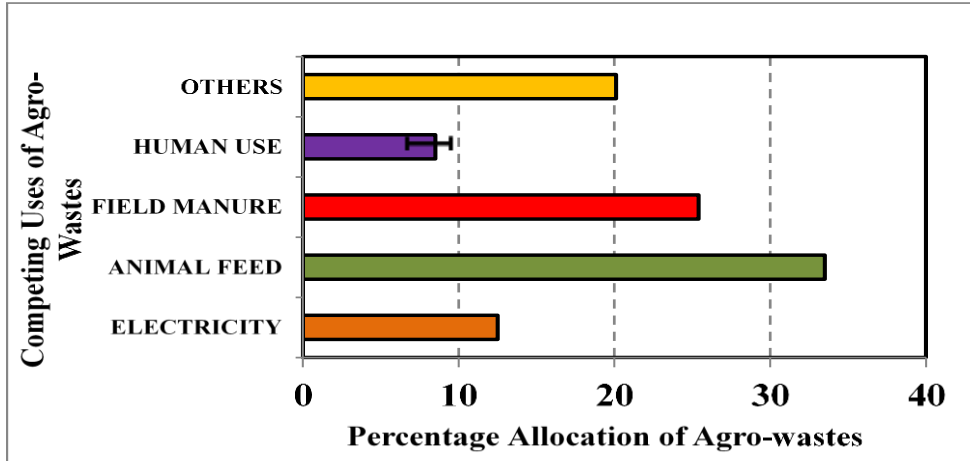


**Figure 11:** Column Plot of Calorific Value of each Major Agro-Waste in Northeast

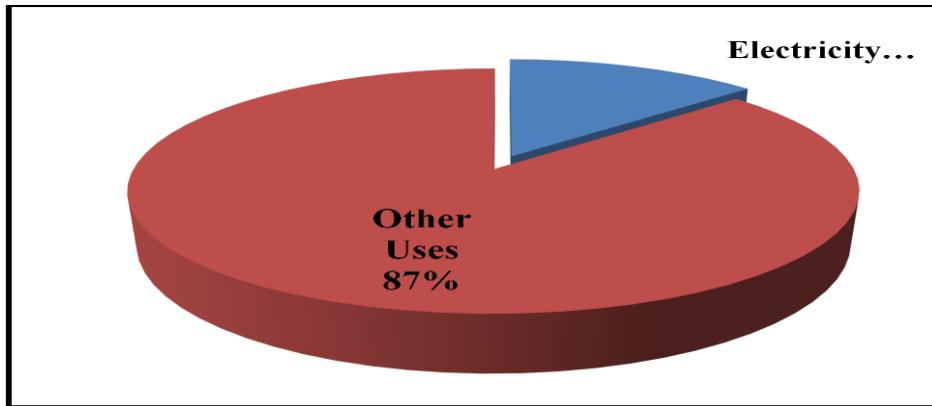
### 3.3 Results of agro-waste allocation via Linear Programming (LP) approach

The total agro-wastes generated in the northeast have been shared in pareto-optimal sense amongst competing users via the bar chart of (Figure 11) that deployed hybrid Monte-Carlo greedy simulation engine. The range of permissible values for each competing users must be specified a-priori to enable the determination of the pareto-optimum sharing ratio of the agro-wastes as found by the algorithm for the assumed competing users of agro-wastes. (Figure 12) depicts the percentage allocation of agro-wastes to the competing candidates assumed; whilst (Figure 13) is a pie-chart illustration of the percentage of allocation to electricity generation against the share allocated to other major competing needs of agro-wastes in northeast sub-region of Nigeria.





**Figure 12:** Bar Chart Representation of Agro-Waste Resource Allocation in Northeast



**Figure 13:** Pie-Chart Comparison of Agro-Wastes Allocation to Electricity versus Other Uses

Table 2 presents the results of weighted proximate analysis that enabled the computations of calorific values for the agro-residues from the major crops grown in the northeastern Nigeria. Table 3 offers, in the main, the range of calorific values obtained for the dominant agro-wastes admitted in this paper. This table has also presented energy worth for each agro-waste type to enable gross estimation of overall energy yield from all agro-wastes. Table 4 has comprehensively summarized the leading results of the LP based resource allocation of agro-wastes in the northeast.

**Table 2:** Energy Derived from the Eight Selected Agro Wastes in MJ/Kg

S/No	Sample	Proximate Analysis Weighted Variables for NE							Calorific Value (CV)	
		% <i>DM</i>	% <i>MC</i>	% <i>CP</i>	% <i>EE</i>	% <i>CF</i>	% <i>ASH</i>	% <i>CBH</i>	Kcal/kg	(MJ/kg)
1	S/C. Bagasse	28.4	2.5	24	4	41.1	28.4	2.5	3904	16.34
2	Maize Cob	7.5	8.5	8	3.5	72.5	7.5	8.5	3960	16.57
3	Millet Bran	7.5	17.4	2.8	2.2	70.1	7.5	17.4	3752	15.7
4	Beans Pod	14.2	6.7	16	4.5	58.6	14.2	6.7	4052	16.96
5	Sorghum Bran	8	2.5	2.9	2.3	84.3	8	2.5	3733	15.62
6	G/Nut Shell	7.8	4.3	3.5	6	78.4	7.8	4.3	3623	16.14
7	Wheat Husk	4.85	2.9	6	2	84.25	4.85	2.9	4026	16.85
8	Rice Husk	15	13	13	15	44	15	13	3450	14.44

**Table 3:** Energy Contents of Eight Agro-Wastes Utilizing Their Annual Estimations & LHV

S/N	Major Agro-wastes in NE	Total Annual Agro-Waste. (MTx10 <sup>7</sup> )	Lower Calorific Value (LHV) MJ/Kg			Weighted Calorific Value TOE/Kg x10 <sup>-3</sup>	Total Energy Content	
			Min LHV	Weighted LHV	Max LHV		TOE x10 <sup>7</sup>	PJ
1	Sugar Cane Bagasse	7.469	14.25	16.34	17.04	0.39	2.913	1219.61
2	Maize Cob	1.470	15.01	16.57	17.24	0.396	0.582	243.67
3	Millet Bran	1.203	14.52	15.7	16.25	0.375	0.451	188.82
4	Beans Pod	4.233	15.59	16.96	17.72	0.405	1.714	717.62
5	Sorghum Bran	1.946	14.66	15.62	15.29	0.373	0.726	303.96
6	Groundnut Shell	0.565	15.01	16.14	16.98	0.385	0.218	91.27
7	Wheat Husk	8.813	16.21	16.85	17.25	0.402	3.543	1483.38
8	Rice Husk	5.064	13.2	14.44	15.96	0.345	1.747	731.43

**Table 4:** Summary of Main Results of LP Based Resource Allocation of Agro-Wastes

S/No	Competing Users of Agro-waste residues	Specified a-priori parameters		Optimum Value of sharing parameter $\alpha_{OPT}$	Share of Agro-wastes	
		$\alpha_{min}$	$\alpha_{max}$		Amount	unit
1	Animal Feed	0.30	0.65	0.335	17.1x10 <sup>4</sup>	MT/yr
2	Electricity Generation	0.08	0.20	0.135	6.89x10 <sup>4</sup>	GWh/yr
3	Human Use-cooking, rural housing	0.06	0.25	0.085	4.34x10 <sup>4</sup>	MT/yr
4	Field Manure	0.35	0.70	0.254	12.96x10 <sup>4</sup>	MT/yr
5	Other Uses in rural shelters, soil stabilization, etc	0.13	0.3	0.191	9.75x10 <sup>4</sup>	MT/yr

We reiterate that dry samples of eight agro-wastes were characterized for each state via proximate analysis. This has enabled the computation of weighted lower heating calorific values for the entire NE, here referred to as benchmark values, as presented in Table 4. It can be inferred from Table 2 that the lower calorific heating values for the admissible agro-wastes in NE

fall within the range of 14.44MJ/kg to 16.96MJ/kg with beans pod returning the highest LHV value of 16.96MJ/kg and rice husk has the least LHV of 14.44MJ/kg. The aforementioned range have been compared with equivalent published values in national and international journals for the agro-wastes analyzed and found to return percentage deviations of  $\pm 5\%$  from published benchmark values for other geographical jurisdictions.

The observed variations in calorific values of corresponding crop residues compared could be rationally linked to differences in ecological zones, chemicals applied, types of crop seedlings planted, etc. Table 3 presents a compendium of energy contents of the agro-wastes computed utilizing their known respective gross estimations and corresponding lower heating values also captured in the table. Referring to comparison of gross energy contents for eight major agro-wastes in the northeast depicted in Figure 11, it can be seen that wheat husk has the highest annual content value of  $3.5 \times 10^7$ TOE or 1483PJ, followed by Bagasse agro-waste bearing annual energy content of  $2.9 \times 10^7$ TOE and the least being groundnut shell that can yield annual energy content of  $0.22 \times 10^7$ TOE. The estimated huge energy potential of 118.9MTOE or 4.98XJ from agro-wastes in northeast is therefore evident, part of which can be utilized for electricity generation.

The formulation of agro-waste allocation as LP problem has been solved and the results obtained presented in Table 4 and further elucidated in (Figures 12 and 13). Referring to Table 4, it is seen that the optimal sharing ratio allocated to electricity generation is 0.135 (13.5%) of the total agro-wastes of the northeast sub-region. The aforementioned percentage corresponds to gross estimates of  $6.89 \times 10^4$  metric tons per annum as agro-wastes available for electricity production and found to be capable of sustaining generation of electrical energy of 55.8GWh/annum for geographically scattered rural communities in the northeast sub-region. A cursory look at (Figure 12) reveals that the highest percentage of agro-wastes, corresponding to 34%, is allocated as animal feed followed by field manure allocated 25% and the least being 8.5% allocated to human use. Indeed, the contribution of this work is anchored on the mathematical model developed to resolve competing usage of agro-wastes in the northeast. As a closure, (Figure 13) is a pie-chart comparison of what has been allocated for electricity generation respect to other identified applications of agro-wastes in the northeast.

#### 4. Conclusion

This research work has comprehensively investigated, in the first phase, the potentials of agro wastes, for distributed electricity productions in Northeast sub-region of Nigeria. Solid biomass, comprising forestry woods and agricultural wastes, is commonly utilized in all the six states of the northeast sub-region as the indigenous energy sources of the rural dwellers. Undoubtedly, agro wastes are the cheapest renewable energy resources found in the northeast sub-region. Based on structured questionnaires administered, it is established that Adamawa state is highest in the sugarcane production whilst Borno state is highest in the production of Rice and wheat. According to Lake Chad Basin Authority, Borno state has a total cultivated area of 45,000 hectares of land with an estimation of  $337.5 \times 10^6$  metric ton per annum of rice production and a gross estimate of  $157.5 \times 10^6$  metric ton of wheat per annum. More precisely, samples of 8 agro-wastes investigated were characterized via proximate analysis which yielded their respective lower heating values to be within the range of 14.44MJ/kg to 16.96MJ/kg. It has been experimentally determined that some of the agro wastes have higher calorific values than others

as documented chronologically in Tables 2 & 3 and Figure 11. The calorific values obtained are within the range compared with existing work done in Nigeria and other countries. Relying on pragmatic solution of LP problem formulation, we arrived at gross estimates of  $6.89 \times 10^4$  metric tons per annum as agro-wastes available for electricity productions of 55.8GWh/annum for geographically scattered rural communities.

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