Property Upgrades of Some Raw Nigerian Biomass through Torrefaction Pre-Treatment- A Review

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Abstract
Today, agricultural waste is one of the most common resources in Nigeria that could solve environmental, fuel and energy issues. However, it has some limitations such as low bulk densities, loose and irregular sizes, handling and storage problems, low energy density, reduced fixed carbon, low calorific value, high volatile matter and high moisture content etc. making it difficult to be utilized for fuel. One of the viable and promising technologies to upgrade the properties of raw biomass is through torrefaction technique which is capable of upgrading the combustion and fuel characteristics of biomass, demonstrated from behaviours that are similar to coal during combustion. During this process, about 70% of the initial biomass weight and about 90% of the original biomass energy is obtained as torrefied biomass while the remaining 30% biomass weight and 10% biomass energy is given off. In addition, the presence of moisture content in raw biomass that could aid biological degradation is reduced (< 3% w.b.) while combustion efficiency is being enhanced through upgraded fixed carbon and calorific value (15-25% wt) and reduced volatiles. These upgraded properties makes torrefied Nigerian biomass suitable to be used independently or co-fired in power plants and as an upgraded feedstock for domestic and industrial applications in a developing country like Nigeria. Unfortunately, there is scarce research materials on biomass torrefaction in Nigeria which could be attributed to the cost of acquiring torrefaction plant and other resources for torrefaction characterization which are on the high side. This paper therefore explores and reviews the property upgrades of raw biomass through torrefaction technique. The challenges of biomass energy in Nigeria, torrefaction effects on some Nigerian biomass, equipment used for the analysis of torrefied samples, alongside the torrefaction properties, combustibility indices and their products were examined. The review study concluded that torrefaction technology is a promising technique in Nigeria which is capable of improving and upgrading the quality, energy value and other properties of raw Nigerian biomass and could at the same time serve as an alternative source of energy asides hydropower energy if embraced by the concerned bodies.

Keywords: Biomass, calorific value, torrefaction, equipment, degradation, upgraded

1. Introduction
The increased interest in renewable and alternative energy resources is global because of the concern for energy security, energy sustainability and greenhouse gas emissions [1]. Biomass is currently among the renewable energy resources in use and accounts for approximately 10% of the global annual energy consumption [2]. In Nigeria, wastes from agricultural and processing activities are highly generated and constitutes nuisance to the environment too. However, it is capable of solving environmental, fuel and electricity issues if properly harnessed, unfortunately, we are yet to look through the direction of biomass utilization for energy applications. To minimize environmental challenges, proper replacement of fossil fuel based products with renewable based
products is essential. In addition, increasing biomass use for energy can help reduce greenhouse gas (GHG) emissions and meet the targets established in the Kyoto protocol [3]. These feedstocks (biomass) are mainly made up of agricultural residues such as sugarcane bagasse, crop straws, and corn stover, switch grass, forestry wastes, wood, wastepaper, municipal waste, sawdust, rice husk, cotton stalk and groundnut husk [4-5].

It has been confirmed from past works that biomass could be transformed into gas or liquid fuels via a variety of methods, such as pyrolysis, anaerobic digestion, fermentation and transesterification [6-9]. It could also be utilized as a solid fuel and burned directly for the generation of heat and power through densification or briquetting technique. However, the limitations of biomass utilization for solid fuel are low energy density and low heating value, low fixed carbon content, high moisture content, high volatile matter content, easiness in moisture absorption (hygroscopic), high alkali metal content (Na, K), low chloride content compared to herbaceous biomass, less air for stoichiometric combustion, low combustion efficiency and smoking during combustion, wide variations in sizes, shapes and types (difficulties on handling and storage), and too bulky, not economical to transport over long distances [10]. Technology barriers to their utilization as energy sources is also one of the main constrains of empowering biofuels [11].

In recent times, a sure alternative to raw biomass utilization for both domestic and industrial applications is the torrefaction technique. Torrefaction technique is the thermochemical conversion of raw biomass material with demonstrated numerous merits of upgrading the properties of biomass, and possess a great potential for industrial applications. Torrefaction is not a new technology in some advanced countries because they have been able to embrace it due to its numerous advantages. However, torrefaction technique is still at the research stage in Nigeria probably because of the high cost of acquiring a torrefaction plant coupled with torrefaction characterization instruments such as Elemental and compositional analyser to determine the elements and fibre composition of biomass, Scanning electron microscope to determine the microstructural properties of the torrefied products, thermo gravimetric analyser to provide the thermal stability of biomass, just to mention but a few. Nevertheless, some substantial works have been done on torrefaction pre-treatments of some raw Nigerian biomass using the available materials where research results showed that there is upgrades especially on the calorific value, fixed carbon and some other important properties of biomass being examined [12-14].

This paper review therefore intends to provide an overview on some Nigerian agricultural wastes with a focus on challenges of biomass energy in Nigeria, torrefaction techniques, equipment used for torrefied analysis, products and upgrades through property comparison with torrefied biomass.

2.0 Methodology
2.1 Challenges of biomass energy in Nigeria

Biomass is a natural and an organic non-fossil resource of biological origin. Nigeria is blessed with enormous biological resources including but not limited to energy crops, agricultural crops, wood, charcoal, grasses and shrubs, residues and wastes (agricultural, forestry, municipal and industrial), aquatic biomass and other non-fossil organic matters [15-17]. Nigeria is also rich in human resources with a population of 170 million by the 2006 population census which we envisaged to be close to 200 million currently. It will be logical to conclude that the abundant energy resources should sufficiently sustain the teeming population but this is not so. This is due to the dichotomy in energy use by the urban and the rural household, acceptance for usage and equipment required for biomass energy generation and distribution.
Meanwhile, biomass energy, which is an energy derived from biomass could be produced directly or indirectly in form of biofuel. Direct production of biomass occur via combustion and co-firing while indirect means occur via bioethanol, biodiesel, biogas etc. for further use. Among these, direct combustion and co-firing with coal are currently the dominant technologies, which contribute to more than 90% of the global bioenergy deployment [10].

Biomass has several advantages when compared with fossil coal. For instance, biomass is abundant, secure, environmental friendly and a renewable source of energy in Southwestern Nigeria, which has the capacity of displacing fossil fuels, and reducing greenhouse gas (GHG) emissions. It is not associated with environmental impacts such as oil spills, acid rain, mine and open pits and radioactive waste being fully aware that green plants from which biomass fuels are derived fix carbon dioxide (CO₂) as they grow, so their use does not add to the levels of atmospheric carbon. In addition, using refuse as a fuel avoids polluting landfill disposal [18]. In addition, fuels produced from biomass burns well, are viable and efficient [19]. The low sulphur content of biomass is an added advantage over fossil coal too [20].

However in Nigeria, the use of biomass for heat and power production is often said to be complicated because of the inherent properties of this feedstock. The limitations such as: lower energy density, transportation, handling and storage issues, low bulk density, high moisture content, hydrophilic nature, and low calorific value, which renders raw biomass difficult for energy generation and utilization [19]. These drawbacks make the direct combustion of biomass in power plants for energy production more challenging. These limitations tend to reduce the efficiencies of biomass thermal conversion processes. Therefore, pre-treatment becomes an essential step to upgrade biomass fuel for either stand-alone use [18, 21-22], blending with other biomass [23-24] or blending with coal [14, 25]. With these pre-treatment steps being taken, the energy recovered is still far below the inherent properties of coal which make its utilization and usage difficult and unacceptable [4, 26].

A promising method to convert a diverse range of biomass to energy dense solid fuels, readily suitable for subsequent thermochemical conversion processes is torrefaction technique. For instance, some researchers such as Garba et al. [4] torrefied rice husk, groundnut shell and corn cob; Akinrinola [29] torrefied some four Nigerian woody biomass such as Gmelina arborea, Terminalia superba, Nauclea diderrichii, Lophira alata and a residue, palm kernel expeller (PKE); Oluoti [27] torrefied Alstonia congensis (Ahun) and Ceiba pentandra (Araba). In addition, Fuwape and Faruwa [13], Akande and Olorunnisola [14] and Ibeto et al. [25] torrefied some tropical biomass; Safana et al. [28] torrefied oil palm empty fruit bunches, etc. By means of torrefaction pretreatment, the fuel and chemical properties of the biomass was significantly upgraded through increased calorific value, reduction in the H/C and O/C ratio, intrinsic transformation from hygroscopic into hydrophobic nature and better grindability coupled with less energy requirement for size reduction etc. [4, 12-14, 25].

Unfortunately, there is scarce research materials on biomass torrefaction in Nigeria when compared with the work-done so far on this subject matter in developed countries, which could be attributed to the cost of acquiring torrefaction plant and other resources such as the elemental analyser, thermogravimetric analyser, scanning electron microscope etc for torrefaction characterization. This calls for more researches with possibilities of opening doors for its applications in industries and in providing an alternative means of energy generation asides hydropower which we currently depend on as a nation.
2.2 The Process of Biomass Torrefaction

Torrefaction is a thermochemical conversion of biomass to produce bio-coal. It is sometimes referred to as mild pyrolysis because torrefaction temperature is less than the temperature of pyrolysis pre-treatments. It is as well regarded as roasting [14] or high temperature drying. It is a pre-treatment process typically in the temperature range of 200-300°C [4, 13, 30] to upgrade the properties of raw biomass in an oxygen deficient or nitrogen atmosphere. It is done at low heating rate with residence time of 10 minutes up to 2 hours [4, 14, 25]. The temperature applied in the treatment is lower than in other thermochemical techniques and this indicates that it requires less energy [31]. The process causes the biomass to lose low molecular weight volatile compounds and gases due to the dehydration and decarboxylation reactions of the long polysaccharide chains present in raw biomass [4]. About 70% of the initial biomass weight and about 90% of the original biomass energy is obtained as shown in Figure 1 [10, 32] while the remaining (30% biomass weight and 10% biomass energy) is given off as liquid and gases. The treatment is an innovative process for production of raw materials suitable for energy production [33].

![Figure 1. Typical mass and energy balance of the torrefaction process](image)

The chemistry behind torrefaction involves mainly the removal of oxygen from the biomass structure after exposure to a hot, oxygen-deficient atmosphere.

In recent times, many research works have been extensively carried out on torrefaction technique on some Nigerian agricultural residue using various devices means as shown in Table 1.

| Torrefaction device | Feedstock used | Reference |
|---------------------|----------------|-----------|
| Pyrolyzer           | Rice husk, Groundnut shell and corn cob | [4]        |
| A container on a kerosene stove | Vegetable wastes (cabbage and carrot waste) | [14]    |
| Reactor, electric furnace | Oil palm empty fruit bunches | [28]        |
| Muffle furnace      | Lignite, coconut shell | [25]        |
| Electric fired fixed bed reactor | Wood wastes | [13]        |
| Oven                | Alstonia congensis (Ahun) and Ceiba pentandra (Araba) | [27]        |
| Bench scale reactor, furnace | Gmelina arborea, Terminalia superba, Nauclea diderrichii, Lophira alata and palm kernel expeller (PKE) residue | [29]        |
| Lenton Tube Furnace | Oil palm frond | [12]        |

The devices being adopted by different researchers in Nigeria clearly describe the different means by which torrefaction could be achieved. For instance, in the work of Garba et al. [4], they described the process of torrefaction such that some biomass sample were being placed inside a crucible and inserted into the pyrolyzer. Akande and Olorunnisola [14] in their work carryout torrefaction where some portion of vegetable wastes (feedstock) were roasted on a kerosene stove.
for about 2 hours. Safana et al. [28] used a stainless steel reactor of 150mm length and 70mm internal diameter which was heated by the heat released through an electric furnace where the reactor temperature was monitored by inserting a K-type thermocouple inside the reactor. Ibeto et al. [25] carried out torrefaction by subjecting some samples of lignite and biomass into a programmable muffle furnace. On the other hand, Fuwape and Faruwa [13] placed their wood waste samples into an electric fired fixed bed reactor where the reactor was heated through an electrical circuit while the attached thermocouple was used to read the temperature variation for both the reactor and the furnace. Oluoti et al. [27] carried out torrefaction on two tropical wood wastes: Alstonia congensis (Ahun) and Ceiba pentandra (Araba) using an oven at different temperature and residence time. In the work of Akinrinola [29], torrefaction experiments were carried out using a bench scale reactor being equipped with a three zone horizontal furnace. Sulaimon [12] in his own work torrefied oil palm frond samples using Lenton Tube Furnace. Irrespective of the various torrefaction processes, means and devices being adopted by different researchers, it was observed that the biomass was transformed into a more homogeneous, brittle and more hydrophobic solid product, which typically contains about 70% of the mass and 90% of the energy initially present in the biomass as described in Figure 1. Torrefied biomass also has a brown to dark brown colour of which the property whose physical appearance is close to fossil coal as shown in Figure 2. This colour change is usually evidenced around the temperature of 250-300°C.

Common biomass reactions throughout torrefaction embrace devolatilization, depolymerization, and carbonisation of hemicellulose, lignin, and polysaccharide [34]. Torrefaction of biomass upgrades its physical properties like grindability, pelletability and proximate and ultimate composition [4, 13, 32]. Besides, the properties of torrefied biomass are more uniform compared to those of raw biomass [13]. The carbon content and calorific value of torrefied biomass increases by 15–25% wt, while the moisture content decreases to <3% (w.b.) [4]- this allows for long term storage without degradation.

2.3 Equipment Used In the Analysis of Torrefied Sample
After torrefaction process, it is required that we compare the effects of biomass torrefaction on raw biomass. Some Nigerian researchers have done extensive work in this area, however, the equipment required in torrefaction processes and properties determination are not readily available due to the high cost of acquiring these equipment, thereby making it difficult for more researchers to delve
into this area to produce and characterise torrefied products from raw biomass for domestic and industrial applications. Ordinarily, many of the characteristics of these biomass samples were supposed to be analysed in Nigeria but are usually taken outside the country for analysis at present. Nevertheless, it is pertinent to discuss the major equipment being used for this characterization, they are: thermogravimetric analyser (TGA), Bomb calorimeter, Elemental (CHSN) analyser, and Scanning electron microscope (SEM), Fourier Transform Infrared Spectroscopy (FTIR) among others.

1. Thermogravimetric Analysis (TGA): This instrument is used to determine the thermal stability of biomass/fuel. This is achieved through slow pyrolysis and combustion of samples is usually carried out using a Thermogravimetric Analysis (TA) Instrument. This instrument helps to determine the rate of decomposition/mass loss of biomass/fuel. On the other hand, differential thermogravimetric analysis (DTG) is usually assessed by plotting the rate of decomposition of a sample against temperature and the maximum peak temperatures for pyrolysis and combustion were obtained. The determination of moisture content, volatile matter and ash content could also be obtained from pyrolysis and combustion tests using this device (TGA analyser).

2. Scanning electron microscope (SEM): SEM is used to determine the morphology of the particles present in the biomass before and after torrefaction. The mechanical structure regarding mechanical strength of the torrefied biomass briquettes is set via morphological analysis. SEM, a surface analytical technique generates enlarged geography pictures of a cloth surface 20x to over 100,000x. SEM analysis examines the degree of micro damage ensuing from thermochemical and densification treatments of biomass. The SEM uses a targeted beam of high energy electrons to come up with a range of signals at the surface of the solid specimens. The field emission cathode within the electrode of the SEM provides narrower searching at low also as at high negatron energy, leading to each improved spacial resolution and reduced sample charging and damage. The signals that derive from electron sample interaction reveal information about the morphology of the material making up the sample; they include, texture, chemical composition, crystalline structure, and orientation of materials making up the sample.

3. Bomb calorimeter: This equipment is used to determine the calorific/heating value of biomass (raw and torrefied).

4. Elemental (CHSN/O) analyser: This device is used to determine the ultimate analysis of fuel samples (raw and torrefied). This device helps in analysing the carbon, hydrogen, sulphur, oxygen and nitrogen content of a fuel sample.

5. Fourier Transform Infrared Spectroscopy (FTIR): The functional groups which give the surface chemistry of the raw and torrefied products are usually obtained from FTIR analysis. It is used to determine if biomass samples are made up of alkene, esters, aromatics, ketone and alcohol with different oxygen-containing functional groups such as OH (3600–3000 cm⁻¹), C–H stretching (2860–2970 cm⁻¹), C=O stretching ketone and carbonyl (1722 cm⁻¹), C= C (1632 cm⁻¹), and C–O (1050 cm⁻¹) etc. present in biomass fuel [4].

2.4 Products of torrefaction process

The process of torrefaction produces a brown to black uniform solid product, in addition as condensables (water, organics, and lipids) and noncondensables [34]. During torrefaction, besides the desired torrefied product (the brown to black uniform solid fuel), by-products such as gases (CO₂, CO, and CH₄), condensable organics and water, in addition to ash, original sugar structures,
modified sugar structures and newly formed polymeric structures) are formed as shown in Figure 3. The non-condensable gas product comprises of toluene, benzene and low molecular weight hydrocarbons [35]. The gas product typically contains 10% of the energy of biomass but because of the low heating value of the gas product, its application is limited [10, 35]. The liquid product is brown or black coloured, depending on the torrefaction temperature being applied [36] and consists of condensable components, such as water, acetic acids, alcohols, aldehydes and ketones [32]. The analysis of liquid product from gas chromatography–mass spectrometry (GC–MS) suggests that the main components in the liquid are monoaromatics; small amounts of heterocyclic hydrocarbons are also obtained at a torrefaction temperature as high as 280°C [36].

Figure 3. Products that are formed during biomass torrefaction process [10]

However, from all the products being obtained from the process of torrefaction, the primary and required product is the solid char [34, 37] while the gas and tar yields are ignored during the torrefaction process [38-39]. Therefore, the determination of the evolved gases and tars may not be determined since they are not necessary.

One method of proper utilization of torrefied biomass is by improving their handling and combustion properties through pellets or better still -densification into products of higher density than the original bulk density of the material processed (which is called briquettes), for better logistics and end-use applications [31, 35].

3. Result and discussions
3.1 Properties of raw and torrefied biomass
The property variation of biomass undergoing torrefaction which shows the relevance of torrefaction over raw biomass is shown in Table 2. The colour change to black solid char after torrefaction, saturated moisture content, and the proximate analysis of biomass reveals the properties change in volatile matter (VM), fixed carbon (FC), and ash after torrefaction. Several researchers in Nigeria has performed several experiments by employing torrefaction technique using rice husk, corncob and groundnut shell [4]; Coconut shell [25]; and some Nigerian wood species [29]. Table 2 lists the elemental constituents, volatile matter (VM), fixed carbon contents, ash content, fixed carbon and the calorific value of a variety of biomass species before and after torrefaction.
Table 2. Ultimate analysis, ash content and calorific value (CV) of some raw and torrefied Nigerian biomass.

| Samples                     | FC%     | VM%      | MC%     | Ash%  | C%      | H%      | O%      | N%      | CV(MJ/kg) |
|-----------------------------|---------|----------|---------|-------|---------|---------|---------|---------|-----------|
| Rice husk (Raw)             | 22.01   | 66.00    | 3.81    | 8.18  | 43.83   | 6.76    | 46.07   | 0.93    | 15.81     |
| Torr. Rice husk (300, 60)   | N/A     | N/A      | N/A     | 5.55  | 53.56   | 5.81    | 39.45   | 0.77    | 20.87     |
| Corn cob                    | 21.08   | 64.00    | 5.44    | 9.48  | 45.02   | 6.51    | 45.41   | 0.31    | 17.12     |
| Torr. Corncob (300, 60)     | N/A     | N/A      | 6.41    | 53.91 | 5.63    | 39.01   | 0.29    | 21.92   |           |
| Groundnut shell             | 19.33   | 63.81    | 8.44    | 45.32 | 6.03    | 43.54   | 0.51    | 18.42   |           |
| Torr. Groundnut shell (300, 60) | N/A   | N/A      | 2.02    | 55.00 | 5.29    | 37.70   | 0.51    | 22.66   |           |
| Coconut shell               | 19.40   | 72.90    | 15.98   | 46.60 | 7.10    | 41.80   | 0.32    | 14.10   |           |
| Torr. coconut shell (300, 20) | 38.70  | 61.80    | 1.00    | 68.60 | 1.89    | 12.80   | 0.65    | 26.00   |           |
| PKE                         | 21.00   | 76.10    | 8.90    | 53.60 | 5.10    | 40.80   | 0.50    | 21.00   |           |
| Torr. PKE (290, 30)         | 29.10   | 65.70    | 3.40    | 60.40 | 5.20    | 33.90   | 0.50    | 22.60   |           |
| Nauclea                     | 18.80   | 80.60    | 4.20    | 53.10 | 5.70    | 40.60   | 0.60    | 20.90   |           |
| Torr. Nauclea (280, 60)     | 36.30   | 62.30    | 1.60    | 60.60 | 5.60    | 33.20   | 0.70    | 24.50   |           |
| Wheat straw                 | 17.60   | 74.10    | 6.10    | 42.80 | 4.90    | 51.38   | 0.50    | 17.60   |           |
| Torr. Wheat straw (280, 60) | 30.10   | 52.80    | 3.10    | 64.50 | 5.60    | 29.10   | 0.67    | 20.60   |           |
| Terminalia                  | 17.40   | 80.20    | 6.10    | 48.90 | 5.20    | 45.50   | 0.30    | 19.20   |           |
| Torr. Terminalia (280, 60)  | 25.40   | 68.30    | 1.50    | 58.70 | 5.30    | 35.70   | 0.35    | 21.50   |           |
| Lophira                     | 20.30   | 78.10    | 13.90   | 51.80 | 5.00    | 42.90   | 0.30    | 20.30   |           |
| Torr. Lophira (280, 60)     | 30.20   | 67.60    | 2.60    | 58.10 | 5.50    | 36.10   | 0.28    | 22.60   |           |
| Coal                        | N/A     | N/A      | N/A     | 11.58 | 74.12   | 4.22    | 6.93    | 1.91    | 26.73     |

*N/A= Not available; Torr. = Torrefied; PKE= Palm kernel shell; FC= Fixed carbon; VM=Volatile matter; MC= Moisture content; C=Carbon content; H= Hydrogen content; O= Oxygen content; N= Nitrogen content; Ref = References

As can be seen in Table 2 and Figure 4, observing from all the raw biomass reviewed, the volatile matter (VM) content is high, ranging from 63.81 to 80.6 wt% while its fixed carbon (FC) content is low, ranging from 17.4 to 22.01 wt%. However, due to devolatilization, depolymerization and dehydration process of biomass from torrefaction process of raw biomass, moisture content and light volatiles are being liberated from the biomass materials, therefore, VM in torrefied biomass is decreased (values ranges from 52.8 to 68.3 wt%), whereas FC is increased in the range 25.4 to 38.7 wt% and CV with the range 20.6- 26.0 wt% respectively. The higher the ash contents in a fuel, the lower the heating value [35]. Moreover, the moisture content in biomass is usually higher than that in coal. As a result, the calorific value of biomass is lower than that of coal [35], that is, through torrefaction, there is higher heating value on torrefied biomass as shown in Figure 4.
Furthermore, it was adjudged that torrefaction process makes biomass hydrophobic (does not absorb water) thereby reducing biological/microbial activities which makes it feasible to be stored in a humid environment [4, 25, 30]. This is as shown in Figure 4 which clearly confirm that there is lower moisture presence due to torrefaction process on raw biomass [31]. This lower presence of moisture in torrefied biomass also compares with that of fossil coal in characteristic [4] which allows its usage in a gasifier for electricity generation and for other domestic and or industrial applications.

Figure 4: Fixed carbon, moisture content and calorific value of some raw and torrefied Nigerian biomass.

Figure 5. Volatile matter content of some raw and torrefied Nigerian biomass
Further studies confirm to us that the O/C and H/C atomic ratios in raw biomass is reduced through torrefaction process as shown in Figure 6 [4, 25, 35]. From the raw biomass reviewed, the O/C atomic ratio ranges from 0.761-1.200 while H/C ratio ranges from 0.095-0.154 while for torrefied biomass, the O/C atomic ratio ranges from 0.19 to 0.74 while H/C ratio ranges from 0.028 to 0.110. Since the calorific value of torrefied biomass sample is increased towards the properties of coal, reduced O/C and H/C ratio which was observed is an indication of maximized energy and mass yield of biomass [35, 41]. This reduction upgrades its application through densification (briquettes or pellets) to be used in a gasifier for electricity generation whether independently or through co-firing.

3.2 Combustion Indices

Changes in torrefaction indices are also used to assess the performance and fuel quality of torrefied biomass. The combustion indices are fuel ratio (FR), combustibility index (CI) and volatile ignitability which were calculated using the equations 1 to 3 respectively [42-45].

**Fuel ratio, FR**

$$ FR = \frac{FC_{db}}{VM_{db}} $$  \hspace{1cm} (1)

**Combustibility index, CI**

$$ CI \left( \frac{MJ}{kg} \right) = \frac{CV_{db}}{FR} \times \left( 115 - Ash_{db} \right) \times \frac{1}{105} $$  \hspace{1cm} (2)

**Volatile ignitability, VI**

$$ VI \left( \frac{MJ}{kg} \right) = \left[ \frac{CV_{db} - 0.338 FC_{db}}{VM_{db} + MC_{db}} \right] \times 100 $$  \hspace{1cm} (3)

According to Makino and Tanno [42] and Ohm et al. [43], fuel ratio, FR ranging from 0.5-2.0 are commonly used in coal fired power plants. From the values obtained in Table 3, torrefied coconut shell, nauclea wood dust and wheat straw falls within this range. Other feedstocks outside this range could be attributed to the type of feedstock and temperature and residence time being used. Increasing the temperature and residence time to 300°C and 60 minutes respectively would probably improve their fuel values. This was confirmed through the results obtained by Conag et al. [44] from sugarcane bagasse where the temperature and residence time below 250°C and 75 minutes gave FR values below the standard values.
Table 3: Combustion indices of some raw and torrefied biomass

| Samples           | VM(db)% | Ash (db)% | FC (db)% | CV(db)(MJ/kg) | FR  | CI(MJ/kg) | VI(MJ/kg) |
|-------------------|---------|-----------|----------|---------------|-----|-----------|-----------|
| Coconut shell     | 86.77   | 0.95      | 23.09    | 16.78         | 0.27| 68.5      | 8.74      |
| Torr coconut shell (300, 20) | 62.42   | 1.52      | 39.09    | 26.26         | 0.63| 45.33     | 20.58     |
| PKE               | 83.53   | 3.18      | 23.05    | 23.05         | 0.28| 88.96     | 16.51     |
| Torr. PKE (290, 30) | 68.01   | 5.38      | 30.12    | 23.4          | 0.44| 55.14     | 18.5      |
| Nauclea           | 84.13   | 0.73      | 19.62    | 21.82         | 0.23| 101.79    | 17.19     |
| Torr Nauclea (270, 60) | 63.31   | 1.42      | 36.89    | 24.9          | 0.58| 46.22     | 19.15     |
| Wheat straw       | 78.91   | 8.84      | 18.74    | 18.74         | 0.24| 79.79     | 14.6      |
| Torr. Wheat straw (270, 60) | 54.49   | 17.65     | 31.06    | 21.26         | 0.57| 34.58     | 18.68     |
| Terminalia        | 85.41   | 2.56      | 18.53    | 20.45         | 0.22| 100.93    | 15.5      |
| Torr. Terminalia (270, 60) | 69.34   | 6.4       | 25.79    | 21.83         | 0.37| 60.71     | 18.51     |
| Lophira           | 90.71   | 1.86      | 23.58    | 23.58         | 0.26| 97.74     | 14.92     |
| Torr. Lophira (270, 60) | 69.4    | 6.47      | 31.01    | 23.2          | 0.45| 53.60     | 17.67     |

For the combustibility index, Ohm et al. [43] recommended a value range of 14-23 MJ/kg. The whole torrefied biomass reviewed agrees with the recommended value. Meanwhile, it was recommended that the volatile ignitability should have a specific calorific value of at least 14 MJ/kg [45]. Generally, biomass subjected to torrefaction temperature at between 250-300°C resulted in increase in fuel ratio and volatile ignitability and a decrease in combustibility index. This strongly implies that torrefaction temperature and time strongly affect the combustion indices- FR, VI and CI. This is because these indices are dependent on volatile matter and its conversion to fixed carbon. This concluded that combustibility indices can be used to assess the torrefaction performance and quality of torrefied biomass. Meanwhile, the Nigerian feedstocks being reviewed are capable of being used alternatively in lieu of fossil coal.

4. Conclusion
Nigerian agricultural wastes (biomass) which are generated in bulk especially during harvest season are considered as a viable solution to the energy challenges of Nigeria. From the reviewed papers, torrefaction technique was seen as a pre-treatment process that is capable of upgrading the properties of raw biomass materials towards the properties of fossil coal. This process requires less energy as the temperature (200-300°C) is lesser when compared with other thermochemical process. The results of the proximate analysis showed that torrefaction through devolatilization, depolymerization and dehydration process reduces the volatile fraction while fixed carbon and the calorific value were being increased. Moreover, the moisture content in torrefied biomass is also reduced thereby eliminating biological/ microbial activities and its feasibility for storage in a humid environment. The fuel performance and quality was also assessed through torrefied biomass. In view of these upgrades, torrefaction is a technique capable of providing a clean, stable and renewable energy source for domestic and industrial uses in Nigeria if properly harnessed.

5. Recommendations
1. Government and private owned companies should assist in the acquisition of equipment needed for torrefaction processes and characterisation such as elemental analyser, thermogravimetric analyser, large scale torrefaction reactor, scanning electron
microscope, etc for research purposes. This will help to reduce the stress of conducting analysis which could be carried out in the country if these equipment are available.

2. Increase in studies associated with the transition of research scale torrefaction equipment to commercial scale facilities is equally recommended.

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