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Faculty of Tropical AgriSciences

Assessment of agri residual biomass for energy utilization (A case study of Nigeria)

DISSERTATION THESIS

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Declaration

I hereby declare that I have completed this dissertation thesis entitled "**Assessment of agri residual biomass for energy utilization (A case study of Nigeria)**" independently, except for the jointly authored publications that are included. In the case of such publications, my specific contribution to each publication has been clearly stated in the relevant publication chapter. Furthermore, I confirm that all texts in this thesis are original and that all information sources have been quoted and acknowledged by means of complete references. I also confirm that this work has not been previously submitted, nor is it currently submitted, for any other degree, to this or any other university.

In Prague, 10th September 2025

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Musa Bappah

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Abstract

As global energy demands increase with growing populations and industrialization, the need for alternative energy sources, especially in developing countries, cannot be overemphasized. Fossil fuels, which are commonly used energy sources, contribute significantly to greenhouse gas emissions and environmental degradation. Firewood is the most widely used cooking fuel, especially in rural areas, leading to deforestation and climate change. Nigeria, like many other developing countries, relies on such unsustainable practices. This study explored the potential of converting common Nigerian agricultural by-products (viz; corn cobs, peanut shells, and rice husks) into solid biofuels. These residues are often discarded despite their energy value. The research is aimed at assessing household energy usage, comparing biomass properties to ISO standards, and testing the mechanical and combustion properties of biofuels produced from these by-products. Structured questionnaires and laboratory measurements were used for the data collection. Findings revealed that firewood and charcoal are the dominant household cooking fuels used due to their low cost and availability. However, over 90% of households expressed willingness to adopt renewable alternative energy sources. Among the studied by-products, peanut shells and corn cobs had high calorific value, low ash, and better ignition properties than rice husks. Despite its high ash content and low calorific value, rice husks have less emission during combustion and a high ash melting temperature. The calorific value of all the by-products was improved by thermal treatment (torrefaction), especially those with a low content of ash. With an annual yield of over 5 million tons, investigated by-products have the potential to generate 21.40 TWh of energy, which can contribute to the country's energy mix and reduce the waste and its impact on humans and the environment. While briquettes made from peanut shells and rice husks demonstrated strong mechanical durability, rice husk briquettes present the lowest CO emission concentration. The study confirms the viability of using these agricultural wastes as renewable energy sources, promoting sustainability, reducing environmental harm, and encouraging energy diversification in Nigeria.

Keywords: cooking fuel, briquettes, determinants of choice, torrefaction, rice husk, peanut shells, corn cobs, combustion, energy potential, biomass valorization, solid biofuel properties

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Abbreviations

A_d	Ash content on dry basis
Al	Aluminum
Ca	Calcium
CH_4	Methane
Cl	Chlorine
CO	Carbon monoxide
CO_2	Carbon dioxide
CV	Calorific value
DT	Deformation temperature
EY	Energy yield
FC	Fixed carbon
Fe	Iron
FT	Flow temperature
GCV	Gross calorific value
GDP	Gross Domestic Product
GHG	Greenhouse gas
H_2	Hydrogen
HHV	Higher heating value
HT	Hemisphere temperature
ISO	International Organization for Standardization
K	Potassium
LHV	Lower heating value
LPG	Liquefied petroleum gas
M	Moisture content
Mg	Magnesium
Mn	Manganese
Na	Sodium
NC	North Central
NCV	Net calorific value
NDC	Nationally determined contributions
NE	North East
NGN	Nigerian naira
NGO	Non governmental organization
NO_X	Nitrogen oxides
NW	North West
OPEC	Organization of the petroleum exporting countries
P	Phosphorus
PV	Photovoltaic

REMP	Renewable Energy Master Plan
S	Sulphur
SDG	Sustainable development goals
Si	Silicon
SSA	Sub-Saharan Africa
ST	Shrinkage temperature
SW	South West
TGA	Thermogravimetric analyzer
UNDP	United Nations Development Programme
USD	United states dollar
Vd	Volatile matter content on dry basis
VM	Volatile matter

CHAPTER 1 Introduction

Energy has been a global issue of concern, generating more attention at both national and international levels, affecting both developing and developed countries. This energy challenge is always associated with the increasing global population and industrialization. The challenge, which increased after the pandemic due to economic rebound, became more severe after Ukraine's invasion by Russia in February 2022 (IEA, 2022) and is expected to worsen with the current Middle East crisis (Book et al., 2024), being the largest crude oil exporter in the world (Mehdi, 2021). Despite all these fossil challenges in the global energy sector, the transition towards a sustainable future in trying to meet net-zero emissions is facing other challenges, arising from the complexity of the coordination opportunities and the sharing of strategic knowledge (WEC, 2024).

On its outlook, the Organization of the Petroleum Exporting Countries (OPEC) has forecasted a 24% increase in the global energy demand by 2050, from the current 301 million barrels of oil equivalent per day (mboe/d) to 374 mboe/d (OPEC, 2024). This increase in energy demand cuts across all energy sources except coal, with renewable sources expected to have the highest, as presented in Figure 1.1.

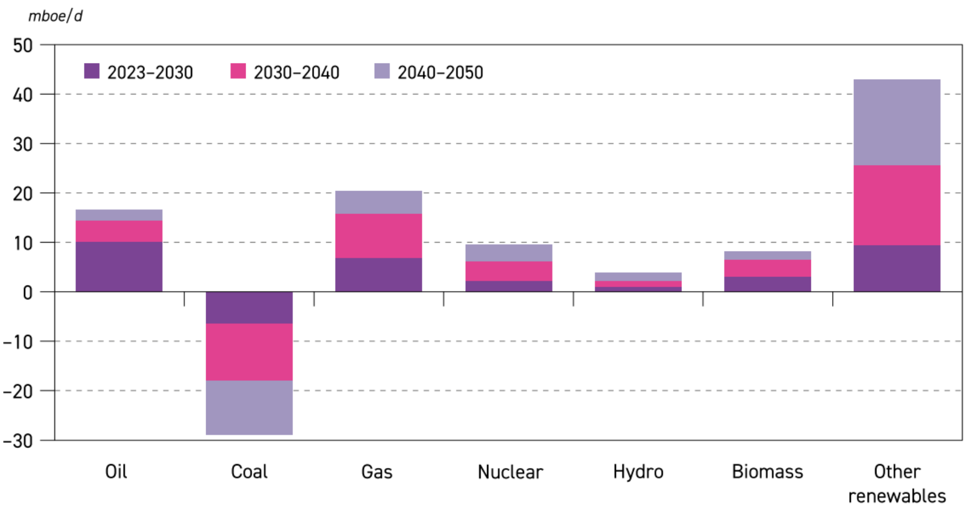

Figure 1.1. Growth in primary energy demand by fuel type, 2023–2050 (OPEC, 2024)

Despite the increase in the demand for renewable energy sources (Mehdi, 2021; OPEC, 2024), oil and gas, which are the main targets for reducing global emissions and policy action (Mehdi, 2021) are expected to continue playing a crucial role in the global energy mix by 2050 (Mehdi, 2021; OPEC, 2024), covering over 53%, with oil share exceeding 29% (OPEC, 2024).

While developed and wealthy countries are significantly subsidising energy to make it available to their citizens at an affordable price despite its high price in the global market, developing countries, with over 80% of the global population, are left with no option but to reduce or completely remove the existing energy subsidies (OPEC, 2024). This will affect the sustainable development goal of ensuring access to affordable, reliable, sustainable and modern energy for all (SDG 7).

About 940 million people were reported to lack access to electricity throughout the world, and over two-thirds were believed to be from Sub-Saharan Africa (SSA) (Adewuyi et al., 2020; Somoye, 2023). This can be appraised as the reason why SSA is considered the region with the highest energy shortage in the world and its industrial development remains impoverished. Similarly, the number of people that are lacking access to clean cooking fuel has doubled those without electricity. Over 3 billion people rely on unclean sources of energy for their cooking (UNEP, 2016). This includes the inefficient use of firewood, agricultural residues and animal dung, among others, through open fire. The use of this unclean fuel is associated with the death of 3.2 million people every year, mostly in developing countries (IEA, 2022; Rosenthal et al., 2018). The provision of clean and reliable energy, coupled with making it affordable to the people, is considered as part of the factors indicating the level of socio-economic development of that community, thereby helping in achieving Goal 7 of the Sustainable Development Goals (SDGs), which is also associated with the achievement of the remaining goals (Adewuyi et al., 2020), as illustrated by UNDP in Figure 1.2.

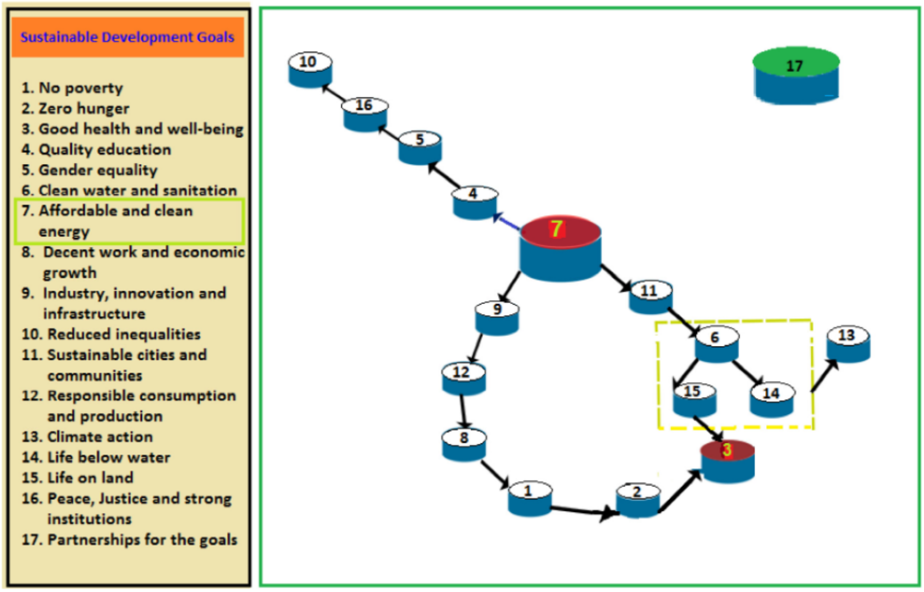

Figure 1.2. SDGs interrelationship network (UNDP, 2015).

There is a rapid increase in energy consumption in developing countries resulting from an increase in their population and economic activities, which is expected to rise according to their development rate (Bilgen, 2014; Kaygusuz & Bilgen, 2008). This energy deficit, which is mostly covered using polluting sources, thereby increasing the emission of unwanted gases and contributing to climate change, affects the well-being of the people and the environment. Exploring renewable energy sources and gradually transitioning to them will reduce the impact of those polluting fuels on both the people and the environment. With the way things are going, the outcome of the energy transition cannot be predicted (Mehdi, 2021; OPEC, 2024).

As one of the great players in the global energy sector and the largest natural gas producer in Africa, with over 200 trillion cubic feet of gas reserves (Energy News Africa Plus, 2024), Nigeria has millions of people who are still living in darkness due to infrastructural challenges, poor maintenance culture and corruption, among other factors (Adhekpukoli, 2018; Somoye, 2023). A large amount of this gas is wasted through flaring instead of proper collection and utilization for energy generation, which can reduce the impact caused by the energy shortage. The gas flaring affects not only human health but also the environment. Moreover, this challenge is not limited to living in darkness, it also affects different sectors of the economy in the country. It increases the cost of goods production and services, as many businesses rely on gasoline or diesel generators for their production (Adewuyi et al., 2020; Adhekpukoli, 2018). This leads to the closure of many businesses and increases the cost of the final products, making it difficult for the common man to afford goods and services. Some businesses solely depend on direct (traditional) biomass combustion, thereby contributing to deforestation and desert encroachment. The potential of the country for attracting investors from all around the world has eventually declined and some of the existing ones have found their way out of the country, thereby increasing the unemployment rate (Energy News Africa Plus, 2024).

Both the power generation, transmission and distribution are not providing enough for the teeming Nigerian population, forcing people to go through many challenges of planned outages (load shedding) and forced outages (voltage collapse), especially outside bigger cities (Adhekpukoli, 2018). With all these, about 60% of Nigerians are not connected to the National grid (Roche et al., 2017). People are therefore always looking for an easier way to provide for their energy needs through diesel, petrol and firewood, resulting in environmental degradation. In its report, WHO stated that over 80% of the cooking fuel used by Nigerians is unclean (World Health Organization, 2023), mostly traditional biomass (ICREEE, 2016). Women and children are reported to be the most affected by the effects of unclean fuel due to the time they spend at home and their involvement in cooking and other household activities. Despite different government policies in its efforts to reduce the traditional use of biomass and charcoal by households, the rate of deforestation is still getting higher (Oyeniran & Isola, 2023) and alternative energy sources are still not getting ground (ICREEE, 2016).

Households are mostly willing to accept alternative cooking energy sources, more especially electricity and LPG, due to their ease of use and the health and safety of the family (Bappah et al., 2024), but are hindered by some factors, including cost and availability (Bappah et al., 2024; Rogers, 2003; Zhu et al., 2022). They prepare using fuels that are cheap and easy to obtain, irrespective of their effect on their health and the environment, even though they are aware of such effects. Changing to alternative ones will therefore be difficult, as they are more expensive and some require technical know-how (EIA, 2024).

Biomass, as a naturally occurring biological substance with a potential for energy utilization, is generated in many countries through different agricultural processes, ranging from production to final processing. A large amount of biomass is utilized in many developing countries of sub-Saharan Africa and South Asia through traditional ways (Coelho, 2012; OPEC, 2024), mostly for cooking and heating houses (OPEC, 2024). The history of utilizing biomass as a source of energy dates back to the history of human beings (McKendry, 2002). It is an organic matter derived from plant materials, having stored energy from sunlight, obtained through photosynthesis, with the ability to regenerate after usage (McKendry, 2002; F. Wang et al., 2021), usually used for heating by direct combustion, densified to produce solid fuel (eia, 2024;

Perea-Moreno et al., 2019), or converted to liquid or gaseous fuels through different conversion processes (eia, 2024).

Biomass is believed to be a sustainable and renewable energy source, but its traditional way of production was unsustainable. It was considered for personal and household usage, mainly for cooking and heating, mostly with low efficiency (Goldemberg & Teixeira Coelho, 2004). People were cutting down trees to get firewood for cooking, using inefficient stoves like 3-stone and open fires. Biomass is easy to use as it do not require further processing before usage. This practice is still common in developing countries (Hou et al., 2019; UNEP, 2016), with over 3 billion people relying on firewood and other agricultural by-products (UNEP, 2016), without considering planting other trees that will serve as a replacement for the cut ones. Many rural people observe this traditional way of biomass or firewood production as their primary source of income, on which they rely for their livelihood (Coelho, 2012).

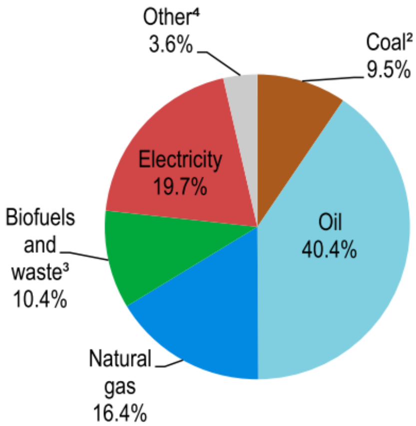

Figure 1.3. World total final energy consumption by source (IEA, 2021).

Biomass plays an important role in the world's energy mix. It accounts for about 10% of the total global energy consumption (Coelho, 2012; IEA, 2021; McKendry, 2002), which can be compared to the contribution of coal (Figure 1.3) (IEA, 2021). This contribution varies from one region to another, as developing regions of Africa, Asia and Latin America were found to use it more than the developed regions (Coelho, 2012; IEA, 2021). As the population of these developing countries is increasing, so is their unsustainable use and demand of biomass (Coelho, 2012).

In general, the global demand for biomass is expected to increase by 8.3 mboe/d through 2050 from 29.1 mboe/d in 2023. This increase will come from the modern use of biomass for biofuel production, including bioplastics, biogas and densified biomass for heating and electricity generation (OPEC, 2024), which is the only way through which its utilization can be improved both in efficiency and in reducing its impacts on human health and the environment (Coelho, 2012). Developing countries, mostly in Asia and Africa, who usually use biomass through traditional processes, are expected to emulate modern utilization, thereby impacting traditional usage (OPEC, 2024). This modern utilization is more pronounced in the industrialised world and is gradually gaining acceptance in the developing world (Coelho, 2012). Despite its importance as an energy source, biomass utilization faces many challenges, ranging from its competition with food production (Ignaciuk et al., 2006; Muscat et al., 2020) to its operational challenges.

Modern use of biomass contributes to both human and industrial sectors and also serves as a source of renewable energy for a cleaner environment. There is an expansion in the modern use of biomass in the area of power generation and biofuel production, both in developed and developing countries, in their effort to provide sustainable energy sources and reduce pollution (OPEC, 2024). This will, therefore, reduce the traditional use of biomass and its impact on the population, especially in developing countries. Despite the industrial development and the increase in the demand for renewable sources of energy, some sectors like aviation and maritime transport systems cannot be handled with renewables (Mehdi, 2021).

Agriculture is the sector contributing to the economic development of many developing countries across the world. Countries like Nigeria have been enjoying the agricultural sector since before the discovery of oil in 1956. It is the only sector in which 70% of the country's population is directly involved, especially those living in rural and sub-rural areas (UNCTAD, 2018; Varrella, 2020). The sector was later neglected and more concern was given to oil, especially during the oil boom of 1973-1988 (Said et al., 2021). Its contribution to the country's Gross Domestic Product (GDP) is around 24% (Oyaniran, 2020). It is the key player in the labour force, covering over 36% of the labour force in the country, thereby making it the largest employer sector, which no other sector can compete with. Crop production is the largest subsector, covering 88% of the agricultural sector (Oyaniran, 2020). Nigerian land supports the production of various cash and food crops due to its land diversity. The major crops grown in Nigeria include cassava, yam, maize (corn), rice, sorghum, millet, groundnut, soybean, cocoa, rubber, palm kernel beans, kola nut and palm oil (Varrella, 2020), from which different biomass, in the form of agricultural waste or by-products, are generated. As the second highest producer in Africa, Nigeria produces about 13 million tons of maize every year (FAOSTAT, 2022; PwC, 2021), 18% of which is the proportion of cobs generated as waste (Blandino et al., 2016). Nigeria also plays a key role in rice and peanut production, where it is positioned as the leading producer in Africa, with an estimated annual production of 8.5 and 4.28

million tons, respectively (FAOSTAT, 2022). Rice husks and straws are the major by-products of rice production, amounting to 43% of the total production (Adeoye et al., 2011). While rice straw is produced onsite and a certain percentage is used for feeding animals, rice husk, which constitutes 20% of the total produce, is produced off-site during paddy processing and is often discarded or burned (Goodman, 2020). Just like rice husk, peanut shells are also the main by-product obtained from peanut production, which is around 25% by weight of the produce (Adeoye et al., 2011), mostly considered as waste.

Some of the by-products are used as the ingredients for animal feed, while others, like corn cobs, rice husks and groundnut (peanut) shells, are mostly discarded or burned, without deriving any benefit other than polluting the environment (Bappah et al., 2019). Exploring the potential of this biomass is key to environmental protection, value addition, as well as sustainable energy generation. Both solid, liquid and gaseous biofuels can be generated from biomass through different technological processes, including thermochemical (Tursi, 2019; F. Wang et al., 2021), chemical (F. Wang et al., 2021), bio-chemical and physico-chemical conversion processes (Table 1.1). The conversion process can be determined by the quantity and quality of the biomass, as well as the intended output (Tursi, 2019).

The thermo-chemical conversion process involves the use of heat to transform the chemical content of the biomass into usable bioenergy. This method of conversion is classified into 4 processes: gasification, pyrolysis, liquefaction and combustion (Tursi, 2019).

Table 1.1. Biomass main conversion technologies and their corresponding products

Process/Technology		**Feedstock**	**Usable end product**
Thermo-chemical conversion	*Combustion*	(I) Agricultural residues (II) Woody residues (III) Animal wastes	(I) Heat (II) Electricity
	Pyrolysis	(I) Agricultural residues (II) Woody residues	(I) Pyrolysis oil (II) Producer gas (III) Char
	Gasification	(I) Agricultural residues (II) Woody residues	(I) Producer gas/syngas (II) Liquid fuel (III) Char
	Liquefaction	(I) Agricultural residues (II) Woody residues	(I) Fertiliser/biofuel (II) Syngas (III) Liquid fuel
Bio-chemical conversion	*Anaerobic digestion*	(I) Animal wastes (II) Sewage sludge	(I) Biogas (II) Liquid fuel (III) Electricity
	Fermentation	(I) Agricultural residues (II) Sugar (III) Starch	(I) Liquid fuels (bioethanol)
Pysico-chemical Conversion	*Esterification/transesterification*	(I) Vegetable oils (II) Animal fats (III) Waste oils	(I) Liquid fuels (II) Glycerol

Source: (Lebaka , 2013; Tursi, 2019)

Gasification is the process of syngas production from organic materials through a thermochemical process in a limited amount of air. This process leads to the production of gaseous and solid outputs at a temperature range of 400 °C to 700 °C (F. Wang et al., 2021), with the former called syngas comprising a mixture of different gases including carbon dioxide (CO_2), methane (CH_4), hydrogen (H_2) and carbon monoxide (CO) and the latter called char, mainly the organic fraction, comprising ash and carbon (Molino et al., 2016; Tursi, 2019). Similar to gasification is another thermal conversion process called pyrolysis, which leads to the production of all three forms of fuel (solid, liquid and gas) (Lebaka , 2013; Wang et al., 2021). It involves heating the biomass in an oxygen-free atmosphere at a temperature of 400 to 1000 °C (F. Wang et al., 2021). The final output of the process is bio-oil, charcoal and combustible gas (Kaushika et al., 2016; Tursi, 2019).

Liquefaction involves the use of liquid, usually water, at a temperature range of 280-370 °C and under a high pressure of 10-25 MPa for the conversion of biomass to biofuel. The output of this process is mostly in liquid and solid form. While the liquid crude requires further processing, the solid can be used directly for combustion or as a fertilizer in the farm or garden (Tursi, 2019). Unlike liquefaction, combustion is an exothermic chemical reaction between biomass (fuel) and oxygen, leading to the production of heat, water vapour and carbon dioxide (equation 1.1), usually carried out inside a combustion chamber at a temperature range of 800-1000 °C (Tursi, 2019). It is believed to be the conversion method through which 90% of the overall renewable energy that is obtained from biomass is generated (Tursi, 2019). Harnessing energy from such renewable energy sources through sustainable ways will be a good step toward achieving carbon neutrality (Wang et al., 2021).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{energy} \qquad (1.1)$$

For better conversion and transformation, the physicochemical characteristics of the biomass will guide in choosing the appropriate way of harnessing energy form the biomass. Dry biomass, which are mostly targeted for combustion, are guided by certain parameters as moisture content, caloric value, proportions of fixed carbon and volatile substances, ash content and alkali metal content of the biomass (McKendry, 2002; Tursi, 2019).

Moisture content: For better conversion and utilization, biomass with low moisture content is more appropriate for thermal conversion processes. This reduces the time and energy required for drying, which in turn adds to the cost of the final fuel (McKendry, 2002). High moisture content reduces biomass combustion temperature and can result in incomplete combustion, thereby causing unwanted emissions that may affect human health and the environment (Forest Research, 2019; Toscano et al., 2022; J. Wang et al., 2024). Similarly, erosion of the combustion facility may occur from the re-condensing water in the flue (Forest Research, 2019; J. Wang et al., 2024). However, to densify the biomass for solid biofuel production, the moisture content has to be limited, as it affects the quality of the end fuel (Matúš et al., 2015). For pellet production, the optimum moisture content of the biomass is required to be less than 10% and less than 12% for woody and non-woody biomass respectively (ISO 17225-2, 2021; ISO 17225-3, 2021), while that of briquettes is 12-15% (ISO 17225-6, 2021; ISO 17225-7, 2021). Different moisture contents were reported for various biomass, including wood and non-woody biomass. The moisture content of different agricultural by-products, including peanut shells, rice husk, rice straw and corn cobs, was reported to have a moisture content of 7-9% (Bappah et al., 2019; Erol et al., 2010).

The calorific value (CV) or heating value is the most important parameter used in determining the amount of energy that can be generated from the biomass, upon which the design of the biomass boiler depends (Erol et al., 2010). It is the energy content that will be obtained from the biomass during combustion or burning (McKendry, 2002), which is the easiest and widely used technique for generating heat from biomass material (Erol et al., 2010). It is usually expressed in the quantity of the energy per unit mass or volume of the material (MJ/kg, MJ/l, or MJ/Nm^3) (McKendry, 2002). This CV is usually measured in 2 forms, gross calorific value (GCV) and net calorific value (NCV). GCV is the maximum recoverable energy released by the biomass during combustion, including heat losses to the water (the latent heat of vaporisation), while NCV is the effective usable energy obtained from the biomass after removing the losses. As for woody biomass, the optimum NCV for pellets and briquettes production should be 16.5 $MJ.kg^{-1}$ and 14.9-15.3 $MJ.kg^{-1}$, respectively (ISO 17225-2, 2021; ISO 17225-3, 2021), while that of non-woody pellets and briquettes is set to be 14.5 $MJ.kg^{-1}$ (ISO 17225-6, 2021; ISO 17225-7, 2021).

Just like coal, whose fuel analysis is based on its stored chemical energy in the form of fixed carbon (FC) and volatile matter (VM), other solid fuels, including biomass, follow the same trend. Both FC and VM are used in determining the ease of igniting and gasifying the biomass material (McKendry, 2002). Biomass with high FC and VM are expected to be more easily ignited during combustion than those with lower.

Ash content is the solid residue that remains after the thermal decomposition of biomass (McKendry, 2002; Rosendahl, 2013). It presents one of the main challenges of using biomass for combustion (Munawar et al., 2021). Its presence in large quantities causes problems in the operation of the boiler, thereby reducing its efficiency and causing slag deposits at higher temperatures (McKendry, 2002; Niu et al., 2016). Moreover, handling and management of the ash is another issue which is time and cost-intensive (A. K. James et al., 2012; Munawar et al., 2021), especially those with a high content of heavy metals (Niu et al., 2016). Different biomass has different content and composition of ash, which is an important parameter of concern when it comes to solid biofuel production. As that, for commercial and household use, the ash content of the biomass is set based on the targeted biofuel. For pellets, the ash content of woody and non-woody feedstocks should be 0.7 – 2.0% and 6.0 – 10% respectively (ISO 17225-2, 2021; ISO 17225-6, 2014), while that of woody and non-woody briquettes should not be more than 1.0 – 5.0% and 3.0 – 10%, respectively (ISO 17225-3, 2014; ISO 17225-7, 2021).

The main compositions of ash produced from solid fuel are Silicon (Si), Aluminium (Al), Iron (Fe), Calcium (Ca), Magnesium (Mg), Manganese (Mn), Sodium (Na), Potassium (K), Phosphorus (P), Sulphur (S), and Chlorine (Cl) (Khan et al., 2009; Link et al., 2022; Vassilev et al., 2017). The ratio of basic oxides ($CaO + MgO + Na_2O + K_2O + Fe_2O_3$) to acidic oxides ($SiO_2 + Al_2O_3 + TiO_2$) can be used in determining the sintering tendency of the ash. Higher ratios represent a high sintering tendency of the ash, while low ratios present an indication that the ash is less likely to sinter at high temperatures (Haykiri-Acma et al., 2010). High K_2O content of the biomass is associated with its high tendency to sinter during combustion (Madhiyanon et al., 2009). Alkaline metals, including Sodium (Na), Potassium (K), Magnesium (Mg), Phosphorus (P) and Calcium (Ca), react with some elements like silica during thermal processes to facilitate the melting of the ash inside the boiler, leading to blockage of air passages and causing incomplete combustion. It is therefore an important parameter which needs to be considered when dealing with biomass for combustion purposes (McKendry, 2002).

Bulkiness of biomass is one of the problems hindering its direct utilization as fuel, as it makes handling, storage and transportation so difficult (Ibitoye et al., 2021). Densification, which is less expensive than other conversion processes (IEA, 2019), was discovered to be a promising solution for minimizing storage space requirements and easing transportation and handling by reducing the bulkiness of the biomass (Chico-Santamarta et al., 2012). It is a process that involves applying pressure to compact biomass to form a solid material in the form of briquettes, pellets and bales, with higher energy and bulk density compared to the original material (Ibitoye et al., 2021; N. Mohammed et al., 2023). While pelleting technology uses die and rollers, with the die being flat or ring (Figure 1.4), briquetting technology basically involves the use of piston press, hydraulic press, screw press and roller press (Figure 1.5).

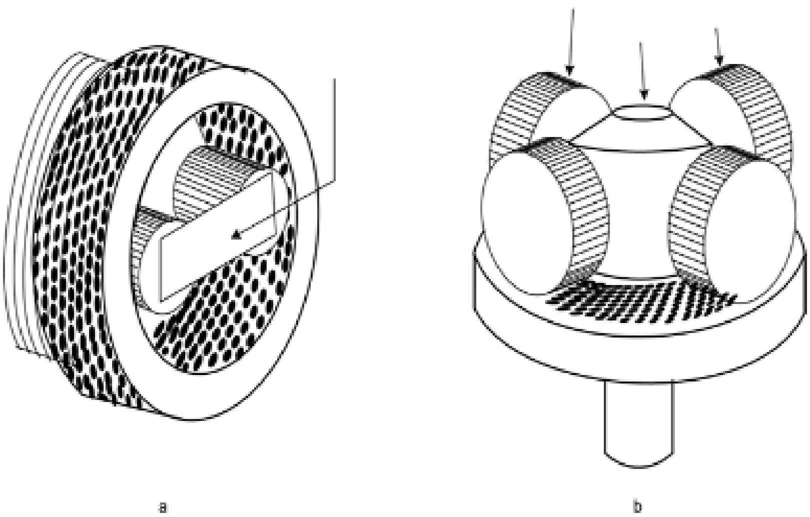

Figure 1.4. (a) Ring die pelletizer and (b) Flat die pelletizer (Koppejan and Van Loo, 2008)

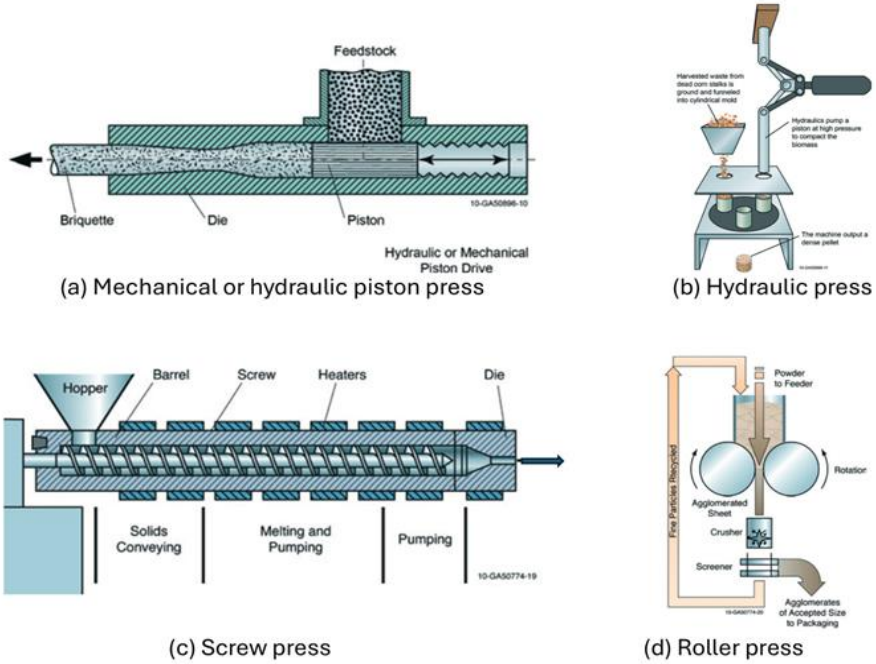

Figure 1.5. Techniques of briquette manufacturing (N. Mohammed et al., 2023; Tumuluru et al., 2011)

Biomass has been proven to be a promising alternative source of energy, which is renewable and considered clean, due to its ability to its carbon neutrality. Among these biomasses are agricultural by-products, obtained from different stages of agricultural activities, ranging from harvesting to final processing. These by-products, especially those with less or no potential for animal feed, are discarded or burned after harvesting or processing, leading to the emission of gases to the atmosphere and wasting a potentially significant amount of energy, which can contribute to the energy mix of many countries if well managed.

This research is therefore aimed at studying some potential Nigerian agricultural by-products for energy production. This involves a comprehensive analysis of their energy characteristics, fuel production and testing the properties of the fuel for better utilization as an alternative source of energy, as well as investigating the sources of energy that are currently used by households in the study area. This will serve as a sustainable way of reducing deforestation by providing an alternative energy source that can be used in place of firewood and help in managing the waste produced from the agricultural sector.

CHAPTER 2 Objectives

2.1. Main objective

The overall objective of this research is to utilize selected agricultural by-products of less importance for the generation of energy that is reliable, sustainable, and eco-friendly. This is to reduce overdependence on fossil fuels and firewood for domestic purposes.

2.2. Specific objectives

1. Determine the sources of energy used for cooking in the study area and the drivers of their choice as fuel.
2. Evaluate the basic fuel-energy properties of abundant biomass materials in accordance with and in comparison to ISO requirements for solid biofuels.
3. Investigate the local utilization of by-products of less quality for energy use.
4. Assess the overall properties and fuel potential of the selected agricultural by-products (rice husks, peanut shells, corn cobs) for possible utilization as alternative cooking energy sources.
5. Improve the energy properties of the studied by-products for better performance as a renewable and alternative source of cooking energy.
6. Test the production of densified solid biofuels from the selected agricultural by-products and analyze their mechanical and combustion properties.

2.3. Relevance of the study

The study is directly linked with the achievement of Goal 7 of the SDGs, which is aimed at ensuring access to affordable, reliable, sustainable, and modern energy for all. It will help in reducing overdependence on firewood and polluting fuels for cooking and heating in developing countries by providing an alternative fuel whose utilization does not require technical know-how. This practice will reduce deforestation and emissions associated problems on women and children, thereby improving the health and well-being of the people, which is the 3rd goal of the SDGs.

2.4. Structure of the dissertation thesis

This dissertation is structured into five main chapters, with each chapter representing a detailed scientific study. The chapters are categorized below:

Chapter 1 provides a general overview of the dissertation thesis.

Chapter 2 outlined the objectives of the dissertation and its overall structure.

Chapter 3 investigates different energy sources that are used for cooking by Nigerian households and their reasons for using them as fuel. This is to ascertain their viability for utilization as feedstock in the production of solid biofuels.

Chapter 4 studies the basic energy properties of 5 selected agricultural by-products (corn cobs, peanut shells, rice husks, sorghum and millet husks) obtained from some of the major crops that are produced in the country, in comparison with different solid biofuel standards and requirements. This is to select the by-products for more detailed investigation in the next chapters.

Chapter 5 specifically explores the utilization of the major rice by-products (husks and straw) by Nigerian farmers due to the great availability of this biomass, but on the other hand, low basic energy quality, regarding combustion properties (i.e., high ash content and low calorific value, as was discovered in Chapter 4).

Chapter 6 deals with the detailed analysis of 3 selected agricultural by-products (peanut shells, corn cobs and rice husks) as solid biofuel feedstocks and looks at the possibility of improving their fuel-energy properties via thermochemical treatment.

Finally, Chapter 7 addresses the solid biofuel production from these 3 agricultural by-products and evaluates their mechanical and thermal properties.

Chapter 8 provides a general conclusion to the dissertation.

Chapter 9 outlined some Recommendations, limitations, and future research directions

CHAPTER 3 Intention to use alternative cooking energy among households of Northeastern Nigeria

Adopted from: Bappah M., Yakubu Madaki M., Alexiou Ivanova T., Garba Abubakar L., Bradna J. (2024). Intention to use alternative cooking energy among households of Northeastern Nigeria. *Energy for Sustainable Development*, 83: 101569. https//doi.org/10.1016/j.esd.2024.101569

Highlights

- Cooking energy is one of the global challenges, especially in developing countries
- Firewood and charcoal are the dominant cooking fuels in Northeastern Nigeria
- Cost and availability drive households toward using traditional biomass for cooking
- Households are willing to adopt electricity, LPG and solar for cooking
- Alternative energy sources should be affordable and easy to use

Abstract

Energy is one of the global challenges attracting more concern at both local and international levels due to its impact on health and the environment. Ensuring accessibility to sustainable, affordable, reliable and modern energy is one of the SDG goals intended to be achieved before 2030. The standard of living of a family is determined by the type of energy and the pattern of its utilization by the households. However, many households in developing countries are not using alternative energy sources despite their abundance and potential. This study investigates the predominant energy sources and drivers of intention to use alternative ones as cooking energy among households in Northeastern Nigeria. Three hundred and thirty-nine (339) households were selected using a multi-stage sampling procedure for the study, and data were collected using a structured questionnaire. The result revealed that firewood and charcoal were the dominant energy sources used for cooking by households (63.13% and 52.37%, respectively) due to their relatively low cost and ease of access. Electricity, LPG, and solar are the cooking energy sources that over 90% of households are willing to adopt as alternatives. The ease of using the alternative cooking energy sources, their availability and accessing energy information via radio, NGOs and universities/research institutions affect the household's intention to use alternative cooking energy sources in a positive way. Ensuring a constant supply of electricity, subsidizing solar PV, making LPG available and affordable to households, providing clean and modern stoves at a subsidised price, and collaborating with universities and NGOs for awareness creation will help reduce

deforestation and over-dependence on firewood, thereby protecting the health and the environment.

Keywords: energy source; cooking fuel; determinants of choice; firewood, polluting fuel; Nigeria

3.1. Introduction

Energy is one of the major global issues of concern due to its health and environmental impacts, with fossil fuels being the dominant. Despite global challenges of pandemics, crises, and other vices that are delaying the implementation of sustainable development goals (Fernandez et al., 2023), many countries are working towards attaining accessibility to sustainable, affordable, reliable, and modern energy to their citizens for the achievement of Goal 7 of Sustainable Development Goals (Ewan, 2023). This includes clean fuel for cooking and other human needs. Energy is considered the major contributor to climate change, accounting for over 60% of the world's total emissions of greenhouse gases (UNEP, 2016). Cooking energy has been a significant challenge, especially in developing countries with no constant electricity or alternative energy source. Wood, charcoal, coal and animal waste are the energy sources upon which over 3 billion people rely for cooking globally (UNEP, 2016), using open fires and inefficient stoves, mostly in closed spaces that are not well-ventilated are reported as common practice (Hou et al., 2019).

This poses significant public health issues and environmental impacts, especially on the health of women and children who are more exposed to emissions from indoor cooking, resulting in heart diseases, pneumonia and different respiratory diseases due to the high number of hours they spend at home (Patel, 2014). Air pollution from households’ indoor combustion of traditional biomass through an unclean process is considered one of the factors affecting the environment and public health (Das et al., 2017). Exposure to traditional biomass fuel inflicts enormous respiratory disorders such as wheezing, dyspnoea, chronic cough and morbidity among women (Pathak et al., 2019). Patel (2014) reported that traditional biomass is the cause of about 3.2 million people’s deaths per year (IEA, 2022; Rosenthal et al., 2018; Sierra Vargas et al., 2012), 237,000 of which are children under five years of age, with developing countries taking the largest share. Exposure to traditional biomass led to the premature death of 2.5 million people in 2020 (IEA, 2022; Sierra Vargas et al., 2012). Though there is a decrease in the number of people using polluting fuel by 36% in 2020 from over half of the global population in 1990 (WHO, 2022), global CO_2 emission has been on the rise by more than 46% since 1990 (UNEP, 2016), 61% of which is from the fuels that are used for cooking by households (Frankowska et al., 2020). The emissions, which drastically decreased during the pandemic period, are now back on track with a 5.6% increase over the pre-pandemic level of 2019 (Liu et al., 2023). These emissions can be reduced by adopting alternative cooking fuels that are more eco-friendly (Ciupăgeanu et al., 2017; Frankowska et al., 2020).

Even though 13% of the global population lives in Sub-Saharan Africa (Ifegbesan et al., 2016), they account for 6% of global energy consumption (IEA, 2021, 2022). This led to an increase in energy demand in Africa, which is twice faster than the global average (IEA., 2019). The transition from fossil fuels to renewable energy can reduce the health and environmental energy impacts because of its sustainability and renewability (Savvanidou et al., 2010; Singh et al., 2014). To achieve the main goal and target, the transition must be fair and should carry everybody along, including Sub-Saharan countries. About 90% of the global bioenergy demand comes from solid biomass, 40% of which is used through inefficient, unsustainable and polluting traditional cooking methods (IEA, 2022; Sierra Vargas et al., 2012). Biofuel is a renewable energy derived from biological materials (IEA, 2022; Savvanidou et al., 2010) that can be used in every sector (IEA, 2022), whose awareness is not well-established among people (Savvanidou et al., 2010).

Nigeria is among the Sub-Saharan countries where the use of traditional biomass has created health and environmental consequences. For example, over 81% of Nigerian cooking energy comes from unclean sources (ICREEE, 2016; World Health Organization, 2023), usually firewood, agricultural residues, and animal dung (ICREEE, 2016). Despite government policies and all efforts on infrastructures to ensure clean cooking energy, emissions from household cooking fuel all over the country have been increasing, and the rate of deforestation is also high in trying to provide for household firewood demand (Oyeniran & Isola, 2023). The government has implemented various policy initiatives to reduce the traditional firewood and charcoal to address the social and environmental challenges associated with its utilization, such as National Forest Policy for sustainable forest utilization (Abubakar, 2022), the promotion of efficient cooking technologies (Stephen, 2020), alternative energy sources and transitioning away from fuel wood program (Eweka et al., 2022). However, despite all the concerted efforts, the use of alternative cooking energy in the country remains inappreciable (ICREEE, 2016).

Previous researches on cooking energy in Nigeria were focused on smaller communities like districts or local government areas (Adelekan & Jerome, 2006; Akeh et al., 2023; Danlami, 2019; E. Okun et al., 2022; Emagbetere et al., 2016), however, conducted studies did not consider households' views on their reason for using the cooking energy they are using (Akeh et al., 2023; Danlami, 2019) despite the importance of having information from wide coverage as well as the households' reason for using it. Research conducted in a broader range mostly relied on secondary data (Ifegbesan et al., 2016; Oyeniran & Isola, 2023) which rarely provides the intended information. Research on households' preferences for alternative cooking energy is scanty, especially in the country's Northeastern part and no attention was given to the intention of households to use alternative cooking energy and the drivers of the intention, despite its paramount importance in the formulation of the policies and programs that will enable households to use the alternative cooking energy sources.

The intention to use a technology like alternative cooking energy can be influenced by the characteristics of the user (the household) such as education level, the attributes of the technology (cooking energy source) such as its affordability, availability, comparative advantage over the traditional biomass fuel and the access to information sources as postulated by diffusion of innovation theory (Rogers, 2003). Considering this, this study bridges these gaps by investigating the predominant cooking fuels, reason and preference for households' choice of cooking fuel and the drivers of intention to use alternative cooking energy sources among households in Northeastern Nigeria. The present study gives answers to i) What are the common cooking energies used by households and the reasons for that? ii) Are the households satisfied with the common cooking energy used? iii) Are the households aware of the alternative cooking energies and what factors influence their intention to use them? The study provides useful information about the predominant cooking energies among households, the reason for using them, the awareness level of households regarding alternative cooking energy, and the drivers of their intention to use them. This will be helpful to ministries of health and environment, environmental NGOs, policymakers and other concerned institutions for creating policies and programs that will facilitate and help the households in the use of alternative cooking energy that will reduce the health and environmental impact of using unclean cooking energy sources.

3.2. Materials and methods

3.2.1. Study Area

The study was conducted in Northeastern Nigeria. The North-East is one of the geopolitical zones in Nigeria comprising six states of Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe (Hamidu, 2022; Ibrahim, 2012), with common social, political, economic and geographical features (Ibrahim, 2012). It is the largest zone in terms of land mass among the six geo-political zones of the country, covering 272,451 km^2 (Ibrahim, 2012; InfomediaNG, 2022a), which is close to one-third of the country's total land area (Ibrahim, 2012). The zone has a population of about 26 million people (InfomediaNG, 2022b), covering about 12% of the country's total population. North-East was selected for the study due to its backwardness in infrastructural development among the six geopolitical zones of the country, resulting from conflict (Hanna et al., 2021) and its energy challenges (Ifegbesan et al., 2016) despite the availability of different sources of renewable energy (sun, wind, water and biomass) in the zone (Adeyanju et al., 2020). Firewood is the dominant energy source that is used for cooking in the zone, especially in rural areas. It was also reported to have the highest number of households that use firewood as cooking fuel among the six geopolitical zones of the country (Ifegbesan et al., 2016), thereby increasing the rate of deforestation and contributing to desertification, soil erosion as well as reduction of biodiversity (Adelekan & Jerome, 2006; Ifegbesan et al., 2016). Just like in other parts of the country and the other developing world, the use of polluting fuel as an energy source for cooking is associated with health challenges, especially for women and children in the North-East geopolitical zone of Nigeria. The government is working with the West African Clean Cooking Alliance to ensure sustainable, affordable and safe cooking fuel by 2030 (ICREEE, 2016). Many laws have been enacted for the control and enhancement of forest reserves from 1897 to date, but the enforcements were not properly assured (Mfon et al., 2014).

3.2.2. Sampling procedure and data collection

The households were selected using a multistage sampling procedure. In the first stage, convenient sampling method was used in selecting three states due to the land mass of the study area and insecurity challenges in some states of the zone. The selected states are Bauchi, Gombe and Yobe (see Figure 3.1).

The sample size was determined using the Cochran sampling method for an unknown population (Cochran, 1997) at a confidence level of 95% with a 0.05 error margin (equation 3.1).

$$n_o = \frac{z^2 \times p \times q}{e^2} \tag{3.1}$$

Where: n_o is sample size; z is confidence level; p is estimated proportion of the population; q is (1 – p); e is desired level of precision

In the second stage, as each selected state has three senatorial zones, two senatorial zones were randomly selected from each of the selected states to form 6 zones for the study, thereby giving the zones an equal chance of being selected in the study. In the third stage, two local government areas were randomly selected from each selected senatorial zone. In the fourth stage, a total of 342 households were selected randomly for the study, 57 households from each senatorial zone. After the data collection, 3 questionnaires were removed during the data cleansing for lack of proper response, resulting in a total of 339 households being involved in the analysis. The data were collected from September to December 2022 using anonymous quantitative structured questionnaires.

The survey questionnaire included households' socio-demographic, farm, and institutional characteristics; in addition, cooking energy sources, their characteristics and the reasons for using them. A separate part of the questionnaire was used to collect information on cooking energy preferences and characteristics of the houses.

The data were collected through a face-to-face interview with the households in the study area by the first author and with the help of trained enumerators, who also made direct contact with the households. The data collected includes the socio-demographic characteristics of the households, type of cooking energy use, their satisfaction with the cooking energy, awareness of alternative cooking energy sources and their intention to use them. The data was sorted, coded and stored using cloud (One Drive) and desktop storage in Excel format to minimise the data loss.

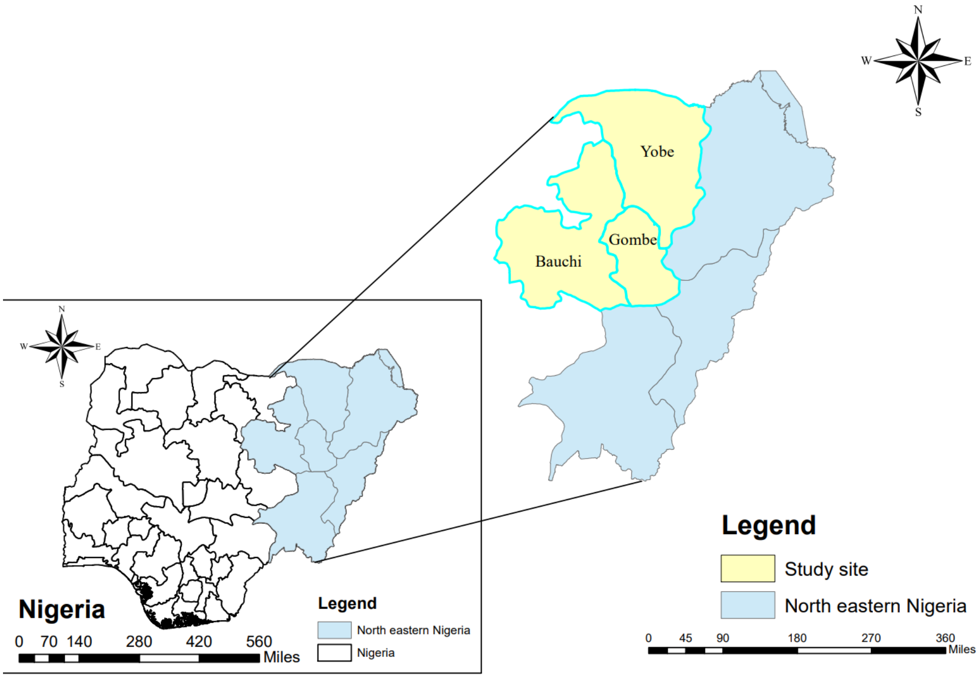

Figure 3.1. Study area (target states of the data collection)

3.2.3. Data Analysis

We analysed the data using descriptive statistical techniques (frequency and percentage) to give a summary description of the study sample and the households' cooking energy. Analysis of the drivers of the intention to use alternative cooking energy among the households was carried out using a logistic regression model. As the dependent variable is measured as a dummy variable, i.e., intention to use alternative cooking sources by the household (Yes = 1, otherwise = 0), this makes a binary logistic regression model appropriate for the analysis (Harrell, 2015). The model fitness is explained using Prob > chi2 result, the potential multicollinearity test between the independent variables was checked using a Spearman Correlation test and Variance Inflation Factor (Appendix 1 and 2). The results of correlation coefficients are weak (<0.60) and none of Variance Inflation factors is greater than 5, which indicates no sign of multicollinearity (Shrestha, 2020).

Household's likelihood to have an intention to use alternative cooking energy is equal to (equations 3.2 and 3.3):

$$Ln(\widehat{Y} \,/\, 1 - \widehat{Y}) \tag{3.2}$$

thus,

$$Ln(\widehat{Y} \,/\, 1 - \widehat{Y}) = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \tag{3.3}$$

Where: $\widehat{Y}$ = dependent variable (1 or 0), α is a constant, $\beta_1 - \beta_n$ are the logistic regression estimates, $X_1 - X_n$ denote the set of socio-demographics of the households, cooking energy characteristics and sources of information that are expected to influence the intention of households to use the alternative cooking energy as postulated by diffusion of innovation theory (Rogers, 2003) and ε is a residual. STATA (version 14) statistical software was used for the analysis. Table 3.1 displays the description of the variables imported into the binary logistic regression model.

Table 3.1. Variables imported into the logistic model

Variable	Description	Mean	Std. Dev.	Min	Max
Dependent variable					
Intention to use alternative cooking energy	Yes = 1, otherwise = 0	0.579	0.495	0	1
Independent variables					
Socio-demographical characteristics					
Age	In years	36.743	10.282	20	70
Gender	Male = 1, female = 0	0.322	0.469	0	1
Household size	Number of people eat from one pot	7.977	4.747	2	31
Education	Years of schooling	14.589	6.998	0	43
Income (NGN/month (USD))[1]	< 30,000 (<$67) = 1 30,000–50,000 ($67–112) = 2 50,001–70,000 ($112–157) = 3 > 70,000 (>$157) = 4	2.673	1.697	1	4
Cooking energy characteristics					
Very cheap	Yes = 1, No = 0	0.687	0.465	0	1
Readily available	Yes = 1, No = 0	0.229	0.421	0	1
Easy to use	Yes = 1, No = 0	0.197	0.399	0	1
Only option	Yes = 1, No = 0	0.136	0.343	0	1
Information sources					
Radio	Yes = 1, No = 0	0.378	0.488	0	1
Television	Yes = 1, No = 0	0.219	0.417	0	1
University/Research Ins.	Yes = 1, No = 0	0.178	0.385	0	1
NGOs	Yes = 1, No = 0	0.096	0.296	0	1
Farmers cooperatives	Yes = 1, No = 0	0.082	0.277	0	1

[1] 1 USD = 445 NGN (December 2022)

3.3. Results and discussion

3.3.1. Sociodemographic characteristics

The result in Table 3.2 indicates that most of the respondent were male between the age of 30–45 years age and most of them were married. This implies that the household heads are in their active age with 5–15 household members. Also, most of the household heads have some high level of education and earn 30,000–70,000 Naira monthly ($67–112). These may have an implication on their intention to use alternative cooking energy as young and educated people are more likely to accept changes than old and uneducated ones as postulated by diffusion of innovation theory (Rogers, 2003). Similar findings report that households with higher levels of education are more likely to accept modern alternative energy sources than those without education (Choumert-Nkolo et al., 2019; Hou et al., 2019).

Table 3.2. Sociodemographic characteristics of the respondents

Variable	Category	Frequency	Percentage
Gender	Male	230	67.85
	Female	109	32.15
Age (years)	< 30	108	31.86
	30–45	170	50.15
	> 45	61	17.99
Marital status	Single	39	11.50
	Married	283	83.48
	Divorced	8	2.36
	Widow	9	2.65
Education	None	10	2.95
	Non-formal	17	5.01
	Primary school	29	8.55
	Secondary school	90	26.55
	College/University	193	56.93
Household size	< 5	143	42.2
	5–10	131	38.6
	11–15	38	11.2
	> 15	27	8.0
Income (NGN/month (USD))	< 30,000 (<$67)	85	25.07
	30,000–50,000 ($68–112)	108	31.86
	50,001–70,000 ($112–157)	60	17.70
	> 70,000 (>$157)	86	25.36

3.3.2. Cooking energy sources used by households

The major fuels used for cooking in the study area are shown in Figure 3.2. While some households use several fuels simultaneously, others use only one. Firewood is the most dominant fuel used for cooking in Northeastern Nigeria. The second most used energy source is charcoal, followed by electricity and LPG; the least used is solar, constituting only 2%. This indicates that the households in the study area use traditional biomass for cooking, which creates serious health and environmental problems. Similar findings were reported in Uganda and Afghanistan, where firewood and charcoal were discovered to be the major cooking fuels (Fahimi & Upham, 2018; Florkowski & Neupane, 2023). Agricultural residue and solar were the least used cooking energy sources in the study area despite their abundance and energy potential. With the diverse agriculture and huge waste by–product generation of Northeastern Nigeria, whose energy potential has been proven (Bappah et al., 2019). The generation of alternative fuel from those abundant by–products will be of less cost and will gain easy acceptance from the households, and at the same time, will gradually overcome deforestation, which has been a major challenge affecting the area. This is a point where the government can create an enabling environment and collaborate with other health and environmental stakeholders to promote the modern use of biomass fuel.

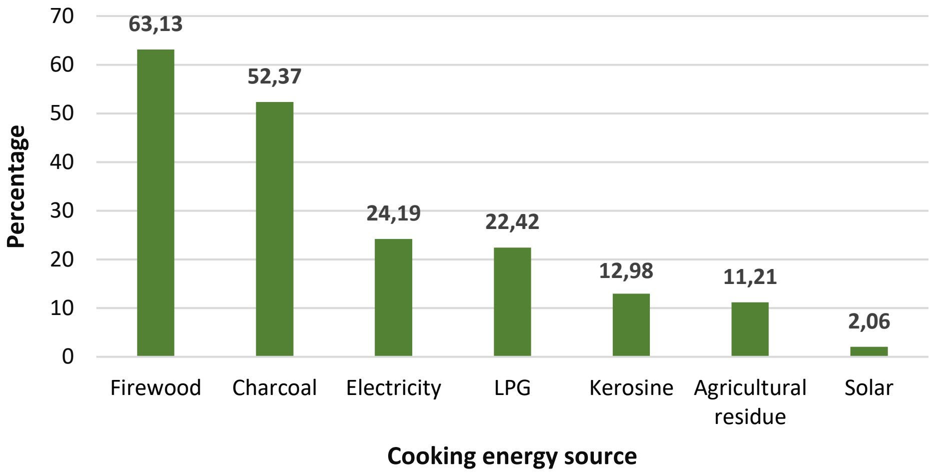

Figure 3.2. Types of cooking energy sources used by households

3.3.3. Reasons for using the cooking energy sources

Figure 3.3 presents the reasons for using cooking energy. Most households consider the cost of fuel as their reason for using it. They used firewood and other polluting fuels because they are cheaper than non-polluting ones (Kowsari & Zerriffi, 2011). Some households use their cooking energy source because it is readily available and to reduce the effects of climate change. Firewood is the most abundant fuel that can be obtained at no or lower cost, making it more preferred and financially feasible to many households (Oyeniran & Isola, 2023). Only a few consider healthcare and the safety of their family as the reason for using their cooking fuel. Despite different policies undertaken by many countries to encourage the use of clean energy for cooking, heating, and other domestic purposes, firewood is yet the dominant energy source used in rural areas. Zhu et al. (2022) reported a similar situation in China. This highlighted the important attribute of energy, which pushes the household to use traditional biomass. This implies that if clean and alternative energy sources are affordable and available to households, they can change their cooking energy sources to alternative ones. Also, as the healthcare and safety of the households are considered less priority attributes of choosing cooking energy source by households, it highlighted the need for awareness on the implication of exposure to traditional biomass cooking fuels, as this will encourage them to use the clean and alternative ones and also avoid the negative effect of the traditional cooking fuel which is the most used cooking energy sources in the area.

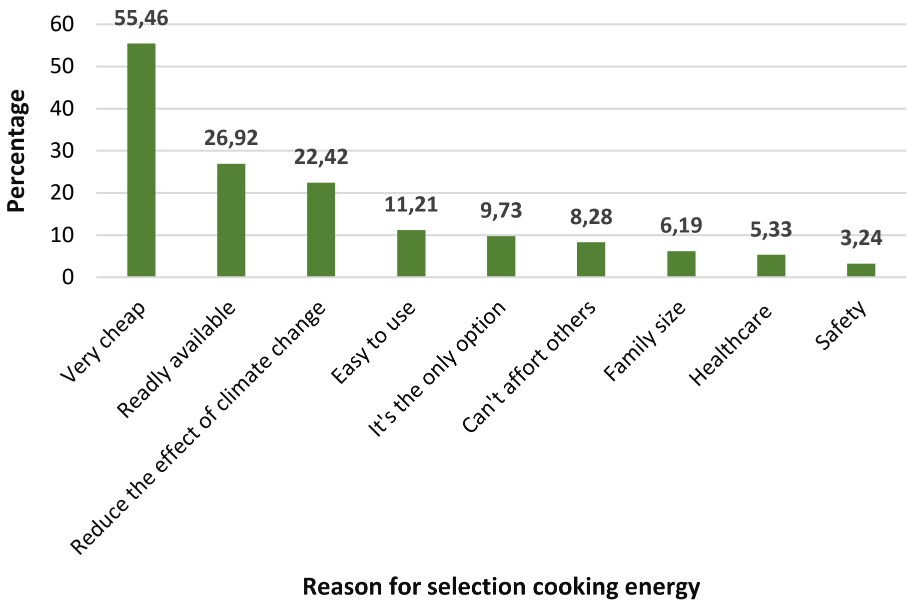

Figure 3.3. Reason for the selection of households' cooking energy

Even though most of the households use firewood as an energy source for cooking (Figure 3.2), more than one-third of them indicated their full satisfaction with its usage (Table 3.3). This implies that most of the households in our sample do not know the negative health consequences of using traditional biomass fuel as cooking energy source despite the proven effect on the lung and respiratory system (Pathak et al., 2019). This highlighted the need for awareness creation on the health and environmental consequences of air pollution (Manisalidis et al., 2020) resulting from using traditional biomass as a source of cooking energy.

3.3.4. Households' intention to use alternative energy sources for cooking

Furthermore, most of the households are willing to accept an alternative energy source (Table 3.3). Electricity, LPG, and solar are the cooking energy sources that most households are willing to adopt as alternatives. Only a few households prefer biofuel as an alternative cooking energy source. This highlighted the need for electricity connection and supply, LPG availability, and policies that will create the enabling environment for solar energy facilitation. A similar finding of willingness to use electricity, LPG and solar was reported by Savvanidou et al., (2010). Willingness to accept changes is a prerequisite for the acceptance of innovation. This will make it easy for the government, health, and environmental stakeholders to facilitate the use of clean and alternative sources of cooking energy.

The result (Table 3.3) further reveals that easy-to-use cooking energy source, family size, and the cost of the energy source are the attributes that drive households towards choosing those alternative sources, as postulated by diffusion of innovation theory (Rogers, 2003). This implies the need for alternative energy source to be easy to use and affordable to facilitate its usage among the households of developing countries like Nigeria.

Table 3.3. Satisfaction with used cooking energy and Intention to use alternative energy sources

Variable	Category	Frequency	Percentage
Are you satisfied with what you are using as an energy source for cooking?	Fully satisfied	139	41.00
	Somehow satisfied	174	51.33
	Not satisfy	26	7.67
Are you willing to accept an alternative source of energy for cooking?	Yes	300	88.76
	No	38	11.24
If yes, which of the energy sources would you prefer?	Firewood (yes)	21	6.91
	Agric. Residue (yes)	18	5.92
	Kerosine (yes)	12	3.97
	Charcoal (yes)	21	6.93
	LPG (yes)	102	33.55
	Solar (yes)	87	28.62
	Electricity (yes)	132	43.42
	Biofuel (yes)	16	5.26
Reason for intention to use the alternative energy source			
Very cheap	Yes	67	21.97
	No	238	78.03
Readily available	Yes	36	11.80
	No	269	88.20
Family safety	Yes	75	24.59
	No	230	75.41
Easy to use	Yes	79	25.90
	No	226	74.10
Health of my family	Yes	54	17.70
	No	251	82.30

3.3.5. Households housing status

Though most of the households have an electricity connection, the majority (about 70%) only enjoy it for less than 12 hours per day (Table 3.4). This may have implication for those who intend to use electricity as an alternative to traditional biomass, as the dark hour may push them to reject it. This implies that the provision of a constant supply of electricity to households and making LPG more affordable to less-income households will reduce the use of unclean energy sources and encourage the transition to cleaner ones. Electricity is the dominant energy source for lighting for over 80% of households, most of which are using it together with other energy sources, mostly batteries (Table 3.3).

More than one-third of the households lived in their personal houses, and another one-third of the sample were living in rented apartments. This may have an implication on the use of clean and alternative cooking energy sources as the households who live in their personal house will be more likely to invest more in installing clean energy facilities like solar and LPG. It was reported that households living in their personal houses are more likely to use LPG as their cooking energy source than those living in rented houses (Akeh et al., 2023).

For the kitchen position with respect to the apartment, more than half of the households have their kitchens attached to the main apartment (Table 3.4). Households with kitchens located away from the main apartments have higher chances of using firewood and other polluting fuels as their cooking energy source than those whose kitchens are attached to the main apartment (Akeh et al., 2023).

Table 3.4. Housing status and electricity use

Variable	Category	Frequency	Percentage
Does your house have an electricity connection?	Yes	321	94.69
	No	18	5.31
How many hours of electricity did you have per day?	0–6 hours	108	32.2
	6.1–12 hours	132	39.4
	12.1–18 hours	49	14.6
	18.1–24 hours	46	13.7
What is the ownership status of your house?	Personal ownership	147	43.36
	Rented apartment	96	28.32
	Government quarters	11	3.24
	Parents/relatives own apartment	82	24.19
	Others	3	0.88
Is your kitchen attached to the main apartment?	Yes	221	65.19
	No	118	34.81
Which energy source are you using for lighting in your house?	Electricity (yes)	274	80.83
	Batteries (yes)	163	48.08
	Kerosine (yes)	26	7.67
	Solar (yes)	48	14.16
	LPG (yes)	6	1.77
	Biofuel (yes)	0	0

3.3.6. Households' perspectives on the consequences of polluting fuels

Results in Table 3.5 display the households’ perception of the consequences of polluting fuels. Most of the households indicate agreement that using firewood for cooking is one of the major causes of deforestation. The collection of firewood from forests and its subsequent utilization as a cooking energy source is among the major causes of forest degradation (Baland et al., 2010; Démurger & Fournier, 2011; Specht et al., 2015). More than half of the households agree that deforestation has a negative impact on the environment. They are, therefore, collecting firewood not because they don’t know the effect of cutting down trees but because of its availability and ease of use. It has been reported that collecting firewood from forests contributes to some environmental problems, including biomass stocking and biodiversity reduction

(Kyaw et al., 2020; Song et al., 2018; Stupak & Raulund-Rasmussen, 2016), thereby affecting the livelihood of the local people (Kyaw et al., 2020).

On the effects of using unclean fuel like kerosene, more than half of the households agree that it affects the health of women and children at home. Even though most households are using traditional biomass for cooking, majority of them agree that using such kind of fuel emits unwanted gasses that have a negative impact on health and the environment. This implies that households are aware of the negative environmental consequences of using traditional biomass. Clean and alternative cooking energy sources should be cheap and available for households to replace the traditional ones, not only to make households aware of the negative effects of traditional cooking energy because the most driving factors are affordability and ease of use.

Table 3.5. Households' perspectives on the consequences of polluting fuels

Variable	Category	Frequency	Percentage
Use of firewood for cooking is one of the major causes of deforestation	Agree	248	73.16
	Uncertain	40	11.8
	Disagree	51	15.04
Deforestation has a negative impact on the environment	Agree	227	66.96
	Uncertain	95	28.02
	Disagree	17	5.01
Utilization of unclean fuel like kerosene affects the health of women and children at home	Agree	219	64.6
	Uncertain	73	21.53
	Disagree	47	13.86
Traditional cooking stoves such as 3-stones and open-fires emit unwanted gasses which have a negative impact on health and the environment	Agree	262	77.29
	Uncertain	60	17.7
	Disagree	17	5.01
Fossil fuels are the major contributors to climate change	Agree	192	56.64
	Uncertain	118	34.81
	Disagree	29	8.55

3.3.7. Drivers of households' intention to use alternative energy sources for cooking

The result in Table 3.6 displays the drivers of households' intention to use alternative cooking energy. The model is significant at 0.001 level which implies that the independent variables imported into the model are good enough to explain the intention of the household to use the alternative cooking energy sources and the Pseudo R^2 (0.334) indicated that 33% variation of intention of households to use alternative cooking energy sources is influenced by the independent variables imported into the model. Regarding the demographic characteristics of the households, only the household size affects the intention of households to use alternative sources of cooking energy. The possible reason why the other socioeconomic characteristics do not have a significant effect on intention in our sample is little heterogeneity of their socioeconomic characteristics, for example age has a mean of 36 and standard deviation of 10, which implies that most of the respondents are between 26–46 years. An increase in household members increases the likelihood of households having the intention to use alternative cooking energy significantly ($p<0.10$). This may be attributed to the fact that households with large family sizes use a huge amount of traditional biomass for cooking, which makes them sense the potential negative health and environmental effects of traditional cooking energy, thereby being more likely to have the intention to use the alternative ones than a household with a small number of people. This is in line with Adeyemi & Adereleye (2016) and Twumasi et al. (2021), who reported the effect of household size on the choice of cooking energy in Nigeria and Ghana.

Table 3.6. Drivers of households' intention to use alternative cooking energy sources

Variable	Coefficient.	Standard error	t-value
Sociodemographic characteristics			
Age	-0.020	0.056	-0.36
Gender	-0.465	0.845	-0.55
Household size	0.167	0.092	1.81*
Education	-0.558	0.467	-1.19
Income	-0.054	0.281	-0.19
Cooking fuel characteristics			
Very cheap	1.21	0.972	1.25
Availability	-1.786	1.191	-1.50
Ease of use	2.953	0.977	3.02***
Only option	2.429	1.04	2.34**
Information sources			
Radio	1.753	0.779	2.25**
Television	-0.659	0.825	-0.80
NGOs	2.059	1.146	1.80*
Universities & research institution	3.612	1.729	2.09**
Famers' cooperatives	0.606	1.564	0.39
Constant	0.805	2.185	0.37
Pseudo R2	0.334		
Number of Observation	339		
Prob > chi2	0.001		

*=p<0.10, **=p<0.05 and ***=p<0.01

Regarding cooking fuel characteristics, as postulated by diffusion of innovation theory (Rogers, 2003), some characteristics of cooking energy sources are found to influence the intention of the household to use alternative source of cooking energy. For instance, ease of use is found to increase the likelihood of households having the intention to use alternative cooking energy sources significantly (p<0.01). This agrees with the diffusion of innovation theory which postulated that technology ease of use is one of the vital attributes promoting the use of technology (Rogers, 2003). This is in agreement with the findings of Emagbetere et al. (2016) who reported the important role of ease of use for choice of cooking energy source in Lagos, Nigeria. Households that use one source of energy for cooking are more likely to have an intention to use the alternative source of cooking energy significantly (p<0.05). The lack of a good supply of multiple clean and alternative energy sources has been reported to be the major factor contributing to the continuous utilization of unclean and traditional biomass as a source of energy for cooking by households in low-income countries (Puzzolo et al., 2019).

Information sources appear to have much effect on the intention to use alternative cooking energy sources. Households that received information on health and environmental issues via radio are more likely to have an intention to use alternative cooking energy sources significantly (p<0.05). This is in line with the Dendup & Arimura (2019) who reported that households that have access to information are more likely to adopt clean energy source in Bhutan. Households that receive information on health and environmental issues through NGOs are more likely to have an intention to use alternative cooking energy sources significantly ($p<0.10$). This is in line with the findings of Van der Kroon et al. (2014) who reported the significant influence of NGOs on household decisions on fuel choice behaviour in Kenya. Likewise, household that receives information on health and environmental issue from universities and research institution are more likely to have an intention to use the alternative cooking energy sources significantly (0.05). Association membership was reported to influence the choice of cooking fuel in Ghana (Twumasi et al., 2021).

3.4. Conclusion

The study has investigated the predominant cooking fuel and drivers influencing the intention of households to use alternative cooking energy sources in Northeastern Nigeria and provided answers to i) What is the common cooking energy source used by households, and the reasons for that? ii) Are the households satisfied with the common cooking energy source used? iii) Are the households aware of the alternative sources of cooking energy and what factors influence their intention to use them, using a quantitative survey.

Almost two-thirds of the households rely on firewood as the energy source for cooking in their houses, and half of them also use charcoal. This implies that the households are using unclean cooking fuel despite their awareness of health and environmental consequences and the concerted efforts of the government. This highlighted that unclean traditional biomass cooking fuel remains dominant in Nigeria and other middle-and-low-income countries. As most of the households are either somehow satisfied or not satisfied, this indicates that most of the households are not satisfied with the dominant unclean traditional biomass used for cooking. Health and environmental stakeholders should use this as an opportunity to facilitate clean and alternative cooking energy sources and motivate households to use them. Most households are aware and willing to use alternative energy sources for cooking. Availability and affordability are the reasons mentioned by the households toward using cooking energy source. With the high agricultural activities in the zone, a lot of by-products are generated, which are mostly discarded or burned in the field. These by-products can be transformed into biofuel in the form of pellets or briquettes and be used as substitute for firewood which can reduce deforestation and maintain the ecosystem.

As the number of people in the house is found to be one of the important socio-demographic drivers that affect the intention of the households to use alternative sources of cooking energy, ministries of health, environment, and other concerned organizations can use this to promote the use of clean and alternative cooking energy sources. That may have a significant impact on public health and the environment as most of the households with large numbers of people burnt huge amounts of unclean and traditional biomass for cooking. Also, ease of use and lack of other alternative cooking energy were found to increase the intention of the households to use alternative cooking energy sources. This indicated that the use of clean and alternative energy sources can be promoted by making them easy to use and available within the communities. Radio, NGOs, universities, and research institutions are the important sources of information drivers found to affect the intention of households to use clean and alternative sources of energy. Policymakers can promote the use of clean and alternative energy sources for cooking by using universities, research institutions, and NGOs to disseminate the side effects of using unclean cooking fuels on health and the environment as well as the merit of using clean and alternative sources of energy via radio.

There is a great opportunity for concerned organizations to reduce the health and environmental consequences of using traditional biomass by making alternative sources of cooking energy easy to use and available at the doorsteps of the household as well as involving the environmental NGOs, universities, and research institutes in awareness creation toward the use of alternative sources of cooking energy to mitigate the negative externalities. As the study used the diffusion of innovation theory to arrive at the possible socioeconomic characteristics of households to influence their intention to use alternative cooking energy sources. This study did not capture all the socioeconomic characteristics of the households like type of dwelling, taste and preference, culture and tradition, which may also have an influence on the intention to use the alternative cooking energy.

Author Contributions

All authors contributed to the design and conception of the study. **Musa Bappah**: Data collection, Methodology, Data Analysis, First draft, Writing - review & editing. **Mustapha Yakubu Madaki**: Methodology, Data Analysis, Writing - review & editing. **Tatiana Alexiou Ivanova**: Methodology, Supervision, Funding acquisition, Resources, Writing - review & editing. **Lawan Garba Abubakar**: Data collection, Methodology, Writing - review & editing. **Jiří Bradna**: Supervision, Writing - review & editing.

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Appendices

Appendix 1: Correlation test of independent variables imported into the model

Variable	Age	Gender	Household size	Education	Income	Very cheap	Readily available	Ease of use	Only option	Radio	Television	University / research ins.	NGOs	Farmers' cooperatives
Age	1.00													
Gender	-0.34	1.00												
Household size	0.43	-0.05	1.00											
Education	0.33	0.10	0.35	1.00										
Income	0.56	-0.23	0.20	0.39	1.00									
Very cheap	-0.08	-0.23	-0.45	0.36	0.11	1.00								
Readily available	0.01	0.03	0.17	0.38	0.05	0.39	1.00							
Easy to use	-0.05	-0.19	-0.19	0.06	0.01	0.26	0.07	1.00						
Only option	0.06	0.13	-0.00	0.08	0.04	-0.04	0.22	-0.23	1.00					
Radio	0.03	0.06	0.19	0.01	0.09	0.05	0.07	-0.02	-0.06	1.00				
Television	0.01	-0.10	0.18	-0.04	0.05	0.24	-0.05	0.48	-0.22	-0.13	1.00			
University/research ins.	0.13	0.04	0.08	0.36	0.19	0.19	0.35	-0.01	0.01	-0.21	-0.08	1.00		
NGOs	0.07	0.14	0.00	-0.15	-0.12	0.04	-0.18	0.14	0.00	-0.25	-0.06	-0.15	1.00	
Farmers' cooperatives	0.09	0.08	-0.10	-0.18	-0.01	-0.08	-0.13	-0.13	0.10	-0.06	-013	-0.11	-0.08	1.00

Appendix 2: Variance inflation factor of independent variables imported into the model

Variable	VIF[1]	1/VIF[1]
Age	2.03	0.493
Gender	1.93	0.517
Household size	1.76	0.569
Education	1.72	0.583
Income	1.65	0.607
Very cheap	1.64	0.608
Readily available	1.57	0.638
Easy to use	1.52	0.656
Only option	1.48	0.676
Radio	1.43	0.698
Television	1.38	0.725
University/research ins.	1.32	0.759
NGOs	1.29	0.775
Farmers cooperatives	1.25	0.798
Mean VIF	1.57	

[1]VIF = Variance inflation factor coefficient

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CHAPTER 4 Viability of some African agricultural by-products as feedstock for solid biofuel production

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Abstract

As a source of renewable energy, agricultural by-products after pre-processing and cleaning in post-harvest lines can be used as a feedstock to produce pellets or briquettes. This can be achieved by determining the physico-chemical properties of the by-products. Groundnut pods (peanut shells), maize cobs (corn cobs) and the husks of rice, millet and sorghum were considered, and their properties were determined, which were then compared with the standard properties of pellets and briquettes to ascertain their viability as a feedstock for the pellet or briquette production. The by-products were transported from Nigeria to the Czech Republic, where laboratory research was conducted. The moisture content, ash content, calorific value, nitrogen content and sulfur content were the properties considered of the by-products. Groundnut pods and maize cobs with a calorific value of 17.48 $MJ.kg^{-1}$ and 16.25 $MJ.kg^{-1}$, an ash content of 3.46% wt. and 1.79% wt., a nitrogen content of 1.24% wt. and 0.44% wt. and a moisture content of 7.92 wt. and 7.56% wt., respectively, were discovered to fulfil all the requirements for graded non-woody pellets and briquettes of the best A class. Except for rice husks and millet husks, which were discovered to have high ash contents and low calorific values, all the by-products fulfilled the standard requirements for one or more grades of pellet/briquette. They can, therefore, be used as a good feedstock for pellet or briquette production.

Keywords: briquette; groundnut pods; maize cobs; pellet

4.1. Introduction

The effects of global warming can be reduced using renewable energy sources such as biomass (McKendry 2002). Agricultural activities, like grain production, are one of the main sources of greenhouse gases (Lenerts et al. 2019). Agricultural by-products are discarded or burned directly on the farm without any processing, leading to the generation of greenhouse gases (Bappah et al. 2019), which can contribute to climate change. The energy value of a biomass material depends on its physical and chemical properties, which include its moisture, ash, organic matter content and elemental composition (Jenkins 2010; Vassi lev et al. 2010; Kraszkiewicz et al. 2015; Akhmedov et al. 2017). Appropriate technologies that can be effectively used for biomass feedstock conversion and their environmental impacts depend on the chemical characteristics of the biomass (Vassilev et al. 2010).

The moisture content is a very important characteristic of the biomass feedstock that always needs to be considered due to its influence on the design, control and optimisation of boiler settings. A higher flue-gas content, longer burn-out time and longer residence time in the boiler are negative aspects associated with a high moisture content with regards to the feedstock (Černý et al. 2016). Usually, the fresh biomass contains about 30–50% moisture (Vassilev et al. 2010). It is, therefore, regarded as one of the most important biomass characteristics, which is considered when determining the energy conversion technology that can be used. A certain amount of moisture is contained in the biomass irrespective of its source or form, which must be reduced to achieve the desired combustion (Jenkins et al. 1998). The moisture content of the raw material should not be too dry or too wet, it must be between 8 and 12% weight (wt.) before passing it into a pellet press, depending on the kind of biomass used (Wang et al. 2012). Though a biomass with a low moisture content is more appropriate for thermal conversion technologies, fermentation and anaerobic digestion are the most appropriate conversion technologies for a biomass with high moisture content (Vassilev et al. 2010).

The ash content is the mass of the inorganic matter remaining after a fuel's combustion under specified conditions (Obernberger et al. 2006; Szem melveisz et al. 2009; Kraszkiewicz et al. 2015), which can suffer considerable variation in its content and composition between the feedstocks, ranging from below 0.5% wt. in dry state/dry basis (d.s./d.b.) in wood pellets to 5–10% wt. in d.s. in agricultural residue, straw and miscanthus. The ash-forming elements and the ash melting point also vary considerably between different biomasses. Silicon, calcium, magnesium, sodium and potassium are the major ash-forming elements, the concentrations of which are of great importance for the combustion characteristics. The temperature at which the ash starts to flow and eventually melt (melting point) leading to slag formation on the grate and in the bed increases with the magnesium and calcium content and decreases with the potassium and sodium content (Nunes 2016; Caraschi et al., 2019). Handling ash is not cost effective, as it must be included in the biomass conversion cost, thereby raising the price of final biofuels (Bradna et al. 2016). Agricultural biomasses are considered to have a higher ash content than wood biomasses, which has a negative impact on both the combustion process and heating value (Bradna and Malaťák 2016).

The calorific value of the biomass is the measure of heat released after combusting the biomass in a controlled environment. The heat released is proportional to the calorific value of the substance (Obernberger and Thek 2004; Hnilička et al. 2015). The calorific value depends on the moisture content of the biomass feedstock, which increases with a decreasing moisture content (Piętka et al. 2019). The type of feedstock used, and the combustion efficiency of the appliance determine the amount of heat that will be produced on combusting the feedstock (Demirbas 2004).

The elemental composition is the content of carbon, hydrogen, oxygen, nitrogen, sulfur and chlorine in the biomass feedstock. Harmful emissions are produced by nitrogen and sulfur during combustion (Kraszkiewicz et al., 2015) and high nitrogen oxide (NO_X) emissions are attributed to the high nitrogen content of the biomass (Díaz-Ramírez et al., 2014; Malaťák et al., 2020a). Due to their negative impact on environment, chlorine, nitrogen and sulfur are undesirable components of fuel combustion, with chlorine and sulfur being corrosive on the technological equipment used for the energy conversion (Winter et al. 1999).

Pelletization is the production of solid materials of uniform shapes and sizes from powdery or coarse material of partly dissimilar particle size (Obern berger and Thek 2004). This involves compressing the milled particles in a flat or vertical mounted die, which binds the pellets by the cohesion of the inner surface, by fibrous parts of particles and primarily by adhesion caused by lignin (Gendek et al. 2018).

Briquetting is one of the oldest techniques which has been used in Europe since the 19th century to make fuel from low-grade peat and brown coals, even though its use for the conversion of agricultural residue is comparatively recent (Gürdil et al. 2009; Gendek et al. 2018). The basic use of a briquette can be to substitute wood and coal, thereby conserving the natural wealth (Chen et al. 2009). The aim of the study is to prove the possibility of using the by-products and waste after the post-harvest pre-cleaning and sorting of special types of crops from different parts of Bauchi state in Nigeria as a source for production of pellets or briquettes with standard EU properties.

4.2. Material and methods

4.2.1. Materials

Representative samples of five different agricultural by-products (rice husks, millet husks, groundnut pods, maize cobs and sorghum husks) were collected from different parts of Bauchi state in Nigeria and transported to the Czech University of Life Sciences Prague, where the laboratory tests were carried out.

4.2.2. Methods

The moisture content of the as received by-products was determined using a UF30 laboratory oven (Memmert, Germany) at a temperature of 105 °C and calculated using equation (4.1) in accordance with the provision of the ISO 18134-3:2015 standard (Hnilička et al. 2015).

$$w = \left(\frac{m_0 - m_1}{m_0}\right) \times 100 \quad (4.1)$$

where: w – moisture content (%); m_0 – mass of the samples before drying (g); m_1 – mass of the samples after drying (g).

A SM100 cutting mill (Retsch, Germany) was used in milling the samples to a 1 mm screen fraction. The moisture and ash content of the samples were determined according to the ISO 18122:2015 standard (International Organization for Standardization 2015), using a TGA701 automated oven (LECO, USA). A AC600 calorimeter (LECO, USA) was used in determining the higher heating values/gross calorific values (HHV/GCV) in accordance with the provisions of the ISO 1928:2020 standard (International Organization for Standardization 2020) and the lower heating values/net calorific values (LHV/NCV) were calculated using equation (4.2) (Pňakovič and Dzurenda 2015).

$$LHV = [HHV - 212w_{Hd} - 0.8(w_{Od} + w_{Hd})] \times (1 - 0.01M_T) - 24.43M_T \quad (4.2)$$

where: LHV – lower heating value ($MJ.kg^{-1}$); HHV – higher heating value ($MJ.kg^{-1}$); w_{Od} – oxygen content in a dry state (% wt.); w_{Hd} – hydrogen content in a dry state (% wt.); M_T – target moisture (0% for a dry state).

The composition of the carbon, hydrogen, oxygen and sulfur in the biomass samples were determined by an ultimate analysis using a CHN628/628S instrument (LECO, USA) (Ivanova et al. 2018; Malaťák et al. 2020b).

4.2.3. Standards

ISO standards ISO 17225-2:2021, ISO 17225-6:2021, ISO 17225-3:2021, ISO 17225-7:2021 (International Organization for Standardization 2021a–d) were used in comparing the properties of the biomass tested with the standard properties of different grades of pellet and briquette to ascertain their viability.

4.3. Results and discussion

The properties of the tested by-products were compared with the international standard limits for graded wood pellets, graded wood briquettes, graded non-woody pellets and graded non-woody briquettes, as presented in Table 4.1 and Table 4.2, respectively.

Table 4.1. Comparison of the properties of the tested graded wood and non-woody pellets with standard values

Property	unit	Graded wood pellets[1]			Graded non-woody pellets[2]	
		A1	A2	B	A	B
Moisture	% wt. o.s.	≤ 10[f]	≤ 10[f]	≤ 10[f]	≤ 12[f]	≤ 15[f]
Ash	% wt. d.s.	≤ 0.7	≤ 1.2	≤ 2.0[d]	≤ 6[cd]	≤ 10[bcd]
Net Calorific Value	$MJ.kg^{-1}$ o.s.	≥ 16.5[c]	≥ 16.5[c]	≥ 16.5[c]	≥ 14.5[cd]	≥ 14.5[cd]
Nitrogen	% wt. d.s.	≤ 0.3	≤ 0.5[bd]	≤ 1.0[abde]	≤ 1.5[f]	≤ 2.0[f]
Sulfur	% wt. d.s.	≤ 0.04[f]	≤ 0.04[f]	≤ 0.05[f]	≤ 0.20[f]	≤ 0.30[f]

o.s. – original sample (or a.r. – as received or w.b. – wet basis); d.s. – dry state; [a]rice husks fulfilled the requirement; [b]sorghum husks fulfilled the requirement; [c]groundnut pods fulfilled the requirement; [d]maize cobs fulfilled the requirement; [e]millet husks fulfilled the requirement; [f]all the by-products fulfilled the requirement; [1]ISO 17225-2:2021 (International Organization for Standardization 2021a); [2]ISO 17225-6:2021 (International Organization for Standardization 2021b)

Table 4.2. Comparison of the properties of the tested graded wood and non-woody briquettes with standard values

Property	unit	Graded wood briquettes[1]			Graded non-woody briquettes[2]	
		A1	A2	B	A	B
Moisture	% wt. o.s.	≤ 10[f]	≤ 10[f]	≤ 10[f]	≤ 12[f]	≤ 15[f]
Ash	% wt. d.s.	≤ 1.0	≤ 1.5	≤ 3.0[d]	≤ 6[cd]	≤ 10[bcd]
Net Calorific Value	$MJ.kg^{-1}$ o.s.	≥ 15.5[bcd]	≥ 15.3[bcd]	≥ 14.9[bcd]	≥ 14.5[cd]	≥ 14.5[cd]
Nitrogen	% wt. d.s.	≤ 0.3	≤ 0.5[bd]	≤ 1.0[abde]	≤ 1.5[f]	≤ 2.0[f]
Sulfur	% wt. d.s.	≤ 0.04[f]	≤ 0.04[f]	≤ 0.05[f]	≤ 0.20[f]	≤ 0.30[f]

o.s. – original sample; d.s. – dry state; [a]rice husks fulfilled the requirement; [b]sorghum husks fulfilled the requirement; [c]groundnut pods fulfilled the requirement; [d]maize cobs fulfilled the requirement; [e]millet husks fulfilled the requirement; [f]all the by-products fulfilled the requirement; [3]ISO 17225-3:2021 (International Organization for Standardization 2021c); [4]ISO 17225-7:2021 (International Organization for Standardization (2021d)

All the tested by-products have a low moisture content of less than 8% wt. in original sample. Maize cobs have the lowest ash content of 1.79% wt. in d.s., followed by groundnut pods and sorghum husks with 3.46% wt. d.s. and 9.08% wt. in d.s., respectively. The net calorific value of the groundnut pods and maize cobs were discovered to be 17.48 $MJ.kg^{-1}$ in the original sample and 16.25 $MJ.kg^{-1}$ in the original sample, respectively, which are the highest among the tested by-products. Compared to the dendromass, where the average combustion temperature of the cone samples is reached at a value of 20.54 $MJ.kg^{-1}$ (Malaťák et al. 2020a) and the herbal biomass, where the combustion temperature is around 18 $MJ.kg^{-1}$ (Vassilev et al. 2010), the values set in the article are at a low level. The nitrogen content, as an element that helps in the production of oxides of nitrogen, was discovered (2016) to be the lowest in the sorghum husks and maize cobs (0.44% wt.) and highest in the rice husks (0.92% wt.). The sulfur content for all the by-products was discovered to be less than 0.05% wt., which is negligible (Juszczak 2016).

The moisture content, as one of the most important characteristics of biomass that needs to be considered when using it as biofuel (Szemmelveisz et al. 2009), was found to be low for all the investigated by-products, which is approximately 7% wt. and satisfied the requirements of all the pellet and briquette categories.

Millet husks were discovered to have a higher ash content (32.16% wt.) which can be attributed to contamination with sand or dust particles during the threshing and sample collection (Pňakovič and Dzurenda 2015; Bappah et al., 2019). The ash content of the rice husks was also found to be 23.58% wt. in d.s., which makes them unfavourable for any pellet or briquette category. Maize cobs were able to satisfy the requirement for both graded woody pellets and briquettes as well as graded non-woody pellets and briquettes, while the groundnut pods and sorghum husks only satisfied the requirement of the non-woody pellets and briquettes (Table 4.3).

Table 4.3. Comparison of the properties of the tested by-products from Nigerian agricultural by-products

Property	Unit	Rice husks[5]	Sorghum husks[5]	Groundnut pods[5]	Maize cobs[5]	Millet husks[5]
Moisture	% wt. o.s.	6.63	7.26	7.92	7.56	5.37
Ash	% wt. d.s.	23.58	9.08	3.46	1.79	32.16
Net Calorific Value	$MJ.kg^{-1}$ o.s.	13.32	14.66	17.48	16.25	11.68
Nitrogen	% wt. d.s.	0.92	0.44	1.24	0.44	0.89
Sulfur	% wt. d.s.	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05

o.s. – original sample; d.s. – dry state; [5]Bappah et al. (2019)

The calorific value, which increases with a decreasing ash content (Bappah et al. 2019), was discovered to be 17.48 $MJ.kg^{-1}$ in the original sample for the groundnut pods and satisfied the requirement for graded woody pellets A1. It can, therefore, be considered as an excellent feedstock for pellet production, judging by its net calorific value and can be used for all the pellet and briquette categories.

All the tested by-products were discovered to have a nitrogen content of less than 1.5% wt. in d.s., which is suitable for all graded non-woody pellet and briquette categories. They can, therefore, be considered as free from emitting any associated nitrogen oxides when combusted (Pňakovič and Dzurenda 2015; Malaťák et al. 2017; Bappah et al. 2019), which are harmful to human health. Except for the groundnut pods, all the tested by-products satisfied the nitrogen requirement for graded wood pellets and briquettes, with the sorghum husks and maize cobs being the best.

Judging by the sulfur content, which is undesirable for fuel combustion due to its corrosive nature on the technological equipment that is used for energy conversion (Johansson et al. 2004; Malaťák et al. 2018), all the by-products have a lower sulfur content than the required maximum for the production of pellets or briquettes.

Due to its availability and the cost required for disposal in most African countries, the viability of rice husks as a feedstock for biofuel production may possibly be improved by mixing it with groundnut pods or maize cobs to increase the energy value and reduce the ash content.

4.4. Conclusion

The properties of some selected agricultural by-products were investigated and compared with the standard characteristics of different grades of pellets and briquettes, to ascertain their viability as feedstocks for solid biofuel production. All the considered by-products were non-woody biomass. Groundnut pods and maize cobs, as by-products with a high energy value and a low ash content, can be used as a good feedstock to produce graded non-woody pellets and graded non-woody briquettes. Though maize cobs also satisfied all the characteristics stated for graded wood pellets or briquettes (of lower B class), groundnuts have higher ash and nitrogen contents when compared to the values of graded wood biofuels. Considering its availability and emissions or cost, which is attached to its disposal, rice husks are recommended to be improved by mixing with maize cobs and or groundnut pods. This may increase its energy value and reduce the ash content so it can be used as a feedstock for solid fuel production. The process can also save the environment from any associated emissions during open burning or disposal.

Author Contributions

All authors contributed to the design and conception of the study. **Musa Bappah:** Data collection, Methodology, Data Analysis, First draft, Writing - review & editing. **Jiří Bradna**: Methodology, Data Analysis, Writing - review & editing. **Jan Malaťák:** Methodology, Supervision, Funding acquisition, Resources, Writing - review & editing. **Petr Vaculík:** Supervision, Writing - review & editing.

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CHAPTER 5 Awareness and willingness to valorize rice by-products for renewable energy: A case study of rice farmers in Nigeria

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Highlights

- Awareness is high, but fewer than half of farmers are willing to adopt energy use
- Older farmers are more willing to adopt despite lower awareness levels
- Competing uses like animal feed and burning reduce interest in energy valorisation
- Larger households face adoption barriers despite greater awareness
- Financial incentives and simple tech can boost adoption of bioenergy practices

Abstract

Rice is a staple food for millions of people around the world and generates significant by-products that often pose environmental challenges if not managed sustainably. Renewable energy utilization of these by-products offers a promising solution to mitigate environmental damage while promoting bioenergy use. This study investigates Nigerian rice farmers' awareness and willingness to adopt energy valorization practices for rice by-products (straw and husks), using survey data from 150 farmers in key rice-producing states. The findings reveal that nearly two-thirds of respondents are aware of energy valorization opportunities, yet less than half are willing to adopt such practices. Competing for rice by-products, including animal feed and reliance on traditional energy sources like firewood and charcoal, significantly influence adoption behavior. Bivariate probit regression analysis identifies key determinants shaping both awareness and willingness to use, including education, household size, farm size, livestock ownership, and dependence on traditional energy sources. The results further underscore the untapped potential of rice husks for renewable energy purposes, as they are more widely utilized compared to rice straw, which is primarily burned or discarded. The study concludes that targeted awareness campaigns, access to affordable energy technologies, and financial incentives are critical to fostering adoption. By promoting renewable energy valorization practices, Nigeria can transform its rice by-product management, reduce environmental degradation, and achieve sustainability within a circular economy framework.

Keyword: rice by-products; renewable energy; energy valorization; bioenergy utilization; circular economy; farmers' awareness and adoption

5.1. Introduction

Rice serves as a staple food for millions of people worldwide, producing substantial by-products such as rice husks, bran, and straw during its cultivation and processing (Abaide et al., 2019; Tan & Norhaizan, 2020; Illankoon et al., 2023). These by-products are often underutilized, discarded, or burned, causing significant environmental challenges, including air pollution and greenhouse gas emissions (Adegbeye et al., 2020; Bhuvaneshwari et al., 2019). Renewable energy valorization presents a sustainable alternative by transforming these residues into valuable energy resources like solid biofuels, biogas, bioethanol, and biochar, reducing waste, and fostering a circular economy in the rice production industry (Hoang et al., 2024; Nguyen & Toan, 2024; Niyogi et al., 2024). This process not only mitigates environmental damage but also promotes economic and social sustainability, particularly in agricultural regions dependent on rice farming.

Rice by-products offer immense potential as renewable biomass resources for energy production through advanced technologies such as gasification, pyrolysis, and anaerobic digestion (Chieng & Kuan, 2022; Singh et al., 2024). These renewable energy technologies facilitate the conversion of by-products into electricity, heat, and liquid fuels, diversifying the energy mix and reducing reliance on fossil fuels (Singh et al., 2024; Abaide et al., 2019). Moreover, bioenergy derived from these by-products aligns with global efforts to combat climate change by lowering carbon emissions (Rashwan et al., 2023; Neogi et al., 2022) and thus in achieving the SDG 13 (climate action). The economic benefits of energy valorization are significant, as it creates new revenue streams for farmers and rice millers, generates rural employment, and enhances energy access in underserved areas (Bhattacharyya et al., 2021; Alengebawy et al., 2023; Rathour et al., 2023). By leveraging rice by-products, stakeholders can address critical issues of energy security, rural economic growth, and environmental sustainability (Rocha-Meneses et al., 2023).

In Nigeria, as Africa's leading rice producer, substantial quantities of rice by-products present significant opportunities for renewable energy valorization (FAO, 2021; Statista, 2022). Technologies like densification, anaerobic digestion and pyrolysis can convert these by-products into sustainable energy forms, addressing the country's persistent energy deficits and environmental concerns (Bappah et al., 2024, 2019; Okafor et al., 2022). Such efforts align with Nigeria's commitments under its Nationally Determined Contributions (NDC) to reduce greenhouse gas emissions (Anyaoha & Zhang, 2021). Furthermore, biochar derived from rice by-products can serve as a soil amendment, enhancing agricultural productivity and fostering a circular economy in the agricultural sector (Okafor et al., 2022; Saravanan et al., 2023). While several policies and studies have explored the potential of bioenergy in Nigeria (NREEEP, 2015; Giwa et al., 2017; Elum et al., 2017). For example, the NREEEP (2015) targets 20% of the country's energy from renewable sources, equivalent to more than 23,000 MW, with biomass expected to contribute 3,200 MW. Number of studies have examined the use of biomass for energy production in Nigeria. These include the conversion of biomass residues and their bioenergy potential (Ezealigo et al., 2021) and the role of agrobioenergy in reducing emissions and mitigating climate change (Elum et al., 2017). Research has also focused on the energy valorization potential of different crops such as oil palm (Anyaoha and Zhang, 2021), maize cobs (Otitolaiye et al., 2021) and further maize residues like stalks and leaves (Mohammed et al., 2020). Other studies investigated the use of cocoa and kola nut residues (Ajewole et al., 2021), carica papaya (Jensen et al., 2020), and the blending of oil palm with municipal solid waste (Salman et al., 2019). Studies on bioethanol production from lignocellulosic biomass feedstocks (Awoyale and Lokhat, 2019) and the calorific value of municipal solid waste (Nwoke et al., 2020) further highlight the potential of bioenergy. Studies also address energy production from municipal solid waste (Ibikunle et al., 2019, 2021), the economic feasibility of waste-to-energy plants (Chukwuma et al., 2021a), and the environmental impact of energy recovery from municipal solid waste (Yusuf et al., 2019). The optimisation of methane emissions for bioelectricity production has also been investigated (Suberu et al., 2013).

Despite this progress and existing technologies, the adoption of rice by-product conversion into energy remains underutilized. Farmers' awareness and willingness to adopt are crucial for utilizing rice residues for renewable energy production; however, the understanding of the drivers is limited (Okoro et al., 2024; Bappah et al., 2024; Rocha-Meneses et al., 2023). This study fills the research gap by investigating factors affecting the awareness rice residues' use for renewable energy production and willingness of rice farmers to use rice by-product for this sake. The study can be useful for policymakers as it provides results and actionable policy recommendations to incentivize farmers to use rice by-products in the study area and similar areas to promote sustainable bioenergy practices.

5.1.1. Nigeria's potential for energy valorization of rice by-products

Nigeria is one of the leading rice producers in Africa, with annual production exceeding 8 million tons (FAO, 2021). This large-scale production generates significant by-products, including rice straw, husks and bran, which account for nearly 50% of the weight of the harvested crop (Ezealigo et al., 2021). However, these residues are often mismanaged: straw is left to rot or burned in the field, while husks and bran are discarded, burned, or used as low-value livestock feed (Ukoba et al., 2023; Sharif et al., 2014). These inefficient disposal practices contribute to serious environmental challenges, particularly air pollution and greenhouse gas (GHG) emissions, which exacerbate climate change (Adegbeye et al., 2020; Bhuvaneshwari et al., 2019).

The conversion of rice by-products into bioenergy provides an opportunity to mitigate these environmental challenges while enhancing economic sustainability. Nigeria's reliance on fossil fuels and poor waste management contribute significantly to greenhouse gas emissions. In 2015, poor waste management alone resulted in 491,000 tons of methane emissions, which are projected to increase to 670,000 tons by 2030 - an untapped energy potential equivalent to 4.74×10^9 kWh (Yusuf et al., 2019). Bioenergy from rice by-products offers a sustainable solution that supports zero waste principles, reduces emissions and promotes economic diversification (Igbokwe et al., 2022). For example, rice husks, which make up 20% of the weight of rice, have an energy content of 14 GJ/ton and can potentially generate 410-570 GWh of electricity annually (Anyanwu, 2022). Similarly, rice straw, which yields 290 kg per ton of rice, can produce 100 kWh of electricity when burned (FAOSTAT, 2020; Ukoba et al., 2023). Though, traditional open burning of these residues exacerbates environmental degradation, advanced technologies such as densification, anaerobic digestion, gasification and pyrolysis can convert these by-products into solid biofuel, biogas, bioethanol and biochar, providing renewable energy alternatives and reducing reliance on fossil fuels.

Nigeria's commitment to clean energy is outlined in its NDCs under the Paris Agreement, targeting a 20-45% reduction in greenhouse gas emissions by 2030. Policies such as the Renewable Energy Master Plan (REMP) and the Biofuel Policy and Incentives (NREEEP, 2015) underscore the country's commitment to sustainability. However, progress in harnessing the potential of bioenergy remains limited. The valorization of rice by-products for energy can address rural electrification deficits, environmental degradation and economic stagnation in farming communities. By integrating circular economy principles, Nigeria can transform agricultural waste into productive assets, thereby enhancing climate change mitigation and energy security. Farmer awareness and adoption of bioenergy technologies is critical to realizing this potential. Sustainable processing of rice husks and straw can improve resource efficiency, reduce waste and produce valuable bioenergy products such as biogas, biochar and bioethanol. These initiatives not only mitigate environmental damage, but also create sustainable economic opportunities, strengthening Nigeria's agricultural resilience and positioning the rice production sector as a model for sustainable development.

5.1.2. Theoretical consideration

Farmers' participation is essential for establishing a sustainable and self-reliant bioenergy sector within a circular economic framework. For this transition to succeed, farmers must be both aware of and willing to adopt renewable energy valorization practices for rice by-products. Various theories have been employed to explain adoption behaviors in this context, including the Diffusion of Innovation Theory (Rogers, 2003; Bappah et al., 2024), the Theory of Planned Behavior (Ajzen, 1985; Almrafee & Akaileh, 2024), and Resource-Based Theory (Kozlenkova et al., 2014). Among these, the Diffusion of Innovation Theory provides a comprehensive framework for understanding how demographic factors, asset ownership, and existing energy practices influence the awareness and willingness to adopt energy valorization technologies. It emphasizes the role of perceived benefits, compatibility, and system observability in shaping adoption decisions.

The Diffusion of Innovation Theory identifies several attributes that drive adoption: relative advantage, compatibility, complexity, trialability, and observability. Relative advantage reflects the perceived benefits of energy valorization over traditional practices, while compatibility assesses alignment with farmers' existing systems and needs. Complexity pertains to ease of understanding and use, trialability refers to the ability to test the innovation on a limited scale, and observability captures the visibility of positive outcomes. Socio-demographic characteristics, such as age, education, and household size, align with these attributes by influencing access to knowledge and resources. Additionally, farm assets and current practices for rice by-product utilization play a significant role in determining adoption readiness and behavior.

This study uses the Diffusion of Innovation Theory to analyze rice farmers' awareness and willingness to adopt energy valorization practices. The findings highlight the importance of socio-demographic factors, such as education, gender, and household size, in determining the capacity to comprehend and adopt bioenergy technologies (Madaki et al., 2023). Access to assets like farm size, livestock ownership, and irrigation systems critically affect farmers' readiness to invest in these innovations (Ali et al., 2020; Amare et al., 2019). Additionally, competing uses for rice by-products, such as animal feed or soil enrichment, influence their perceived relative advantage for energy valorization. Farmers are more likely to adopt these practices when they recognize tangible economic and environmental benefits, addressing misconceptions about costs and technological complexities (Olujobi et al., 2022). The conceptual framework of the study is illustrated in Figure 5.1

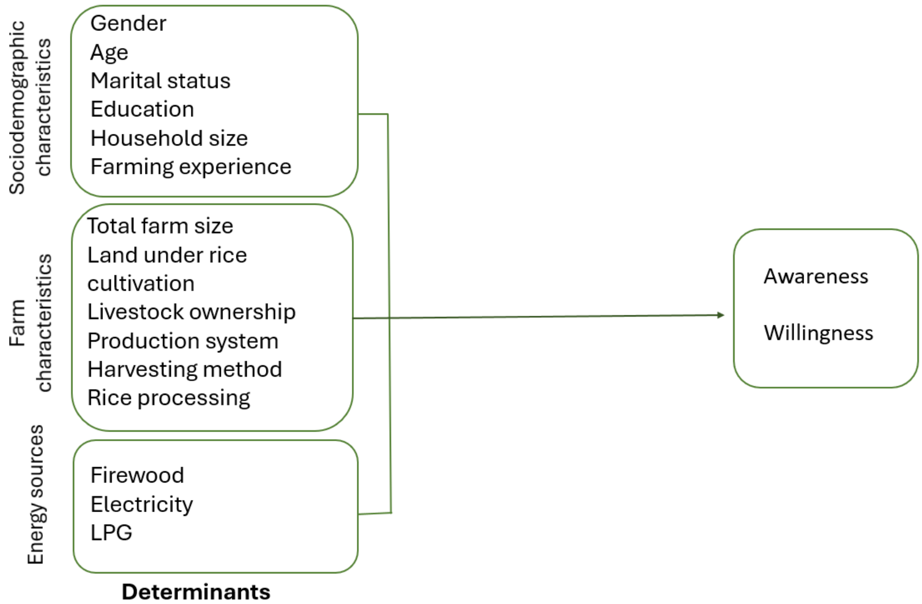

Figure 5.1. Conceptual framework of the study

5.2. Methodology

5.2.1. Study area

Nigeria, a country located in West Africa, is characterized by the presence of six distinct agro-ecological zones: namely, the semi-arid, Sudan and Guinea savannah, rainforest, mangrove, and swamp forest. The country's total land area is approximately 923,768 km², of which approximately 68 million hectares have been designated as agricultural land, including 28 million hectares allocated for pasture and rangeland (FAO, 2021). The country's population was estimated at 206 million in 2020, with nearly half (49.7%) residing in rural areas (Statista, 2021). Rainfall distribution exhibits significant variation, with the southeastern region receiving over 3,000 mm annually, the southwest receiving around 1,800 mm, and the arid northern areas receiving approximately 500 mm. The northern region experiences temperatures reaching 38°C in April and May, with occasional night frosts during the same period (Britannica, 2021). Nigeria is a prominent producer of rice in Africa, with an annual production exceeding 8 million metric tons (FAO, 2021). The nation's varied topography and climate, encompassing wet rainforest zones in the south and Guinea savannah in the north, offer optimal conditions for both rainfed and irrigated rice farming (Odeniyi et al., 2020). Approximately 10% of the country's agricultural land is allocated to rice cultivation, with major production hubs in the North-West, North-East, and North-Central geopolitical zones (Olasehinde et al., 2022).

5.2.2. Sampling procedure

A multistage sampling strategy, involving purposive and convenient sampling techniques, was adopted for the study. This is to maintain safety and feasibility while ensuring representativeness. A structured questionnaire was used for data collection. The questionnaire was developed based on the literature and reviewed by an expert to ensure content validity. A pilot test with five respondents confirmed the face validity of the questionnaire, as items were relevant and clear. Seven states of Nasarawa (North-Central), Ogun (South-West), Niger (North-Central), Kano and Kebbi (North-West), and Gombe and Taraba (North-East) were purposively selected across four geopolitical zones of the country (Figure 5.2). The states were selected based on their significant contributions to the nation's rice production. A convenient sampling technique was used in distributing 50 questionnaires among the rice farmers in each of the 4 geopolitical zones. A total of 200 questionnaires were distributed for the study. Accessibility and willingness of the farmers were considered in administering the questionnaires. To ensure the safety of the participants and researchers, some of the areas that are severely affected by insurgency and insecurity were deliberately excluded.

5.2.3. Data collection

A survey was conducted among 200 rice farmers in key rice-producing states across Nigeria's geopolitical zones during August and September 2022. However, due to security challenges, data collection was facilitated by extension officers. Of the 200 questionnaires distributed, 150 were returned, resulting in a response rate of 75%. A structured questionnaire was employed by two of the authors, with the assistance of four extension officers. This questionnaire comprised both closed and open-ended questions. The questionnaire captured information on a range of subjects, including demographic and farm characteristics, sources of energy for cooking and heating, uses of rice by-products, and farmers' awareness and willingness to adopt rice by-product energy valorization practices.

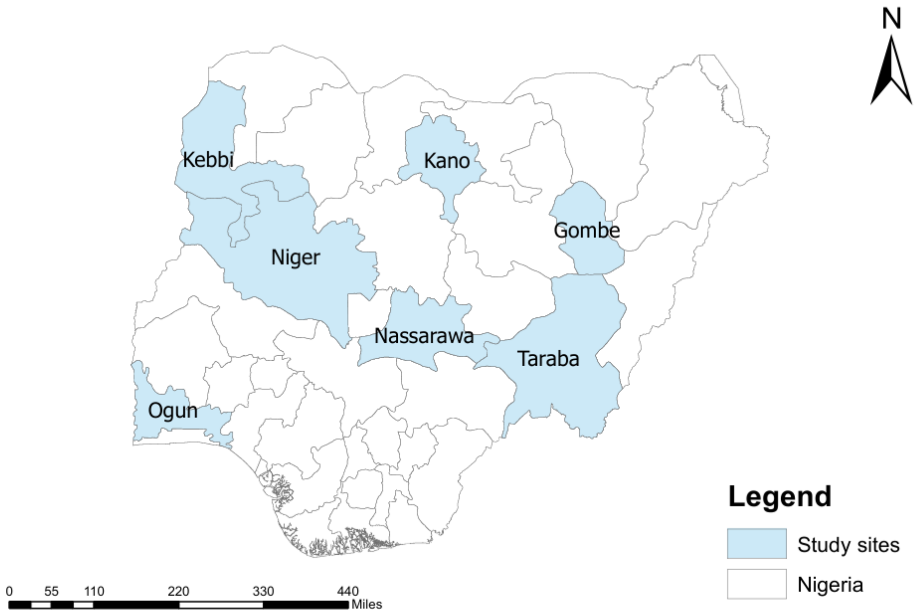

Figure 5.2. Map of Nigeria showing the study sites

5.2.4. Data analysis

Descriptive statistics were utilized to summarize and describe the sample characteristics, while a Bivariate Probit Regression Model was employed to analyze the factors influencing farmers' awareness and willingness to utilize rice residues for energy valorization. The bivariate probit model was specifically chosen to capture the joint determination of two binary outcomes: awareness of and willingness to adopt rice by-product energy valorization. This approach is consistent with its proven effectiveness in analyzing interrelated decisions, as highlighted by Anang et al. (2020) and Ullah et al. (2024). The processing of household survey responses was conducted using STATA version 18, and the bivariate probit model yielded valuable insights into the determinants of awareness and willingness, examining the interaction between these two outcomes. The dependent variables in the model were binary, where a value of 1 represented awareness of rice by-product (straw for cooking as most of the farmers are not using it) valorization or willingness to adopt such practices (using any rice straw or husk for cooking or heating), and 0 indicated a lack of awareness or unwillingness.

The model can be represented using unobserved latent variables (equation 5.1)

$$Y_1 = \beta_1 X_1 + \varepsilon_1 \; Y_2 = \beta_2 X_2 + \varepsilon_2 \quad (5.1)$$

Where:

Y_1 represents the unobserved latent variable for awareness of rice by-product valorization. Y_2 denotes the unobserved latent variable for willingness to adopt valorization practices. X_1 and X_2 are vectors of independent variables influencing awareness and willingness, respectively presented in Table 5.1, β_1 and β_2 are coefficients to be estimated. ε_1 and ε_2 are the error terms, assumed to follow a bivariate normal distribution with a correlation coefficient ρ capturing the potential interdependence between the two decisions. The results from the model offered critical insights into the factors influencing both awareness and willingness, facilitating targeted interventions to promote the adoption of rice by-product valorization practices among farmers.

5.2.5. Variables used in the study

The independent variables for the model were selected based on the Diffusion of Innovation Theory and previous empirical studies and organized into three categories: socio-demographic characteristics, farm characteristics, and energy sources used by rice farmers. Sociodemographic variables such as gender, age, marital status, education level, household size, and farming experience play a pivotal role in influencing farmers' ability to understand and adopt bioenergy technologies (Madaki et al., 2023; Ricart et al., 2025; Halloran et al., 2021). Farm characteristics such as farm size, the extent of cultivated land, livestock ownership, and production systems (rainfed or irrigated) significantly affect farmers' readiness to invest in bioenergy technologies. These factors determine the availability of rice by-products and competing demands for their use, such as feeding livestock or enriching soil (Ali et al., 2020; Amare et al., 2019; Madaki et al., 2024). Farmers already using by-products for traditional purposes may perceive less urgency of transition to alternative energy solutions unless clear benefits are demonstrated (Bappah et al., 2024; Moon et al., 2019). The reliance on traditional energy sources like firewood can reduce the willingness to adopt rice by-products for energy valorization due to familiarity, low-cost accessibility, and cultural preferences.

Table 5.1. Description of the variables imported into the Bivariate probit model

Variable	Description	Mean	Std. Dev.	Minimum	Maximum
Dependent variables					
Awareness	Aware of rice straw for energy valorization (1 = Yes, 0 = No)	0.70	0.45	0	1
Willingness	Willing to use rice by-products for energy valorization (1 = Yes, 0 = No	0.47	0.24	0	1
Independent variables					
Socio-demographic characteristics					
Gender	Male=1, female=0	0.94	0.22	0	1
Age	In years	38.75	10.55	18	70
Marital status	Married=1, single=0	0.70	0.45	0	1
Education	Years of formal education	13.28	3.56	0	18
Household size	Number of people in the house	10.48	9.7	1	47
Farming experience	In years	14.70	9.74	3	50
Farm characteristics					
Total farm size	In hectare	3.91	3.96	0.5	30
Land under rice cultivation	In hectare	2.92	2.34	0.25	15
Livestock ownership	Livestock owners=1, otherwise=0	0.61	0.48	0	1
Production system	Irrigation=1, rainfed=0	0.46	0.50	0	1
Harvesting method	Mechanized=1, manual=0	0.04	0.21	0	1
Rice processing	Yes=1, otherwise=0	0.26	0.44	0	1
Energy sources					
Firewood	Yes=1, otherwise=0	0.57	0.49	0	1
Electricity	Yes=1, otherwise=0	0.09	0.29	0	1
LPG	Yes=1, otherwise=0	0.12	0.34	0	1

5.3. Result and discussion

5.3.1. Description of the study sample

As presented in Table 5.1, the results provide an overview of the demographic characteristics, farm features, and energy sources of the study sample. It is evident that two-thirds of farmers are aware of the potential for utilizing rice by-products for energy valorization; however, less than half are willing to adopt this practice. This discrepancy underscores the necessity for targeted awareness campaigns to educate the remaining one-third of farmers and to provide tailored support to encourage adoption among those already aware. The demographic data reveal that most respondents are male, with an average age of 39 years, and two-thirds of them are married. Most respondents have attained levels of education that exceed high school and have accumulated an average of 14 years of experience in rice farming. The predominance of male-headed farming households may influence awareness and willingness to adopt energy valorization practices. Given the disproportionate impact of inadequate and unclean energy resources on women, their involvement in advocating for and adopting energy valorization practices could prove pivotal.

Regarding farm characteristics, the findings indicate that the farmers have an average farm size of approximately 4 hectares, with about 3 hectares dedicated to rice cultivation. More than half of the respondent's own livestock, less than half employ irrigation systems for rice production, and fewer than 5% use mechanized harvesting methods. The farmers constituting the sample are predominantly small-scale operators, a factor that may influence the utilization of rice by-products. The presence of livestock ownership may compete with the willingness to adopt energy valorization practices, as rice by-products can alternatively be used as animal feed. Conversely, the use of irrigation systems in rice production can enhance the availability of rice by-products for energy valorization, as the by-products are less likely to be damaged by rainfall. However, the prevalence of manual harvesting methods may limit the quantity of rice by-products collected, potentially affecting farmers' willingness to adopt energy valorization practices. In terms of energy sources, most farmers rely on firewood as their primary energy source, followed by LPG and electricity.

5.3.2. Uses of rice by-products by farmers

As illustrated by Figures 5.3 and 5.4, farmers demonstrate a wide range of practices concerning the utilization of rice straw and husk. Notably, approximately one-third of farmers utilize rice straw as animal feed, thereby indicating competition between this use and the practice of energy valorization (Figure 5.3). The analysis further reveals that approximately 30% of farmers resort to burning rice straw, while around 25% choose to discard it. These observations are consistent with the findings reported in the study of Logeswaran et al. (2020) in Malaysia and other Asian countries, and

Bappah et al. (2024) in Nigeria, where large-scale burning and disposal of rice straw among farmers is a common practice. This inefficiency in utilization highlights a significant untapped potential for energy valorization.

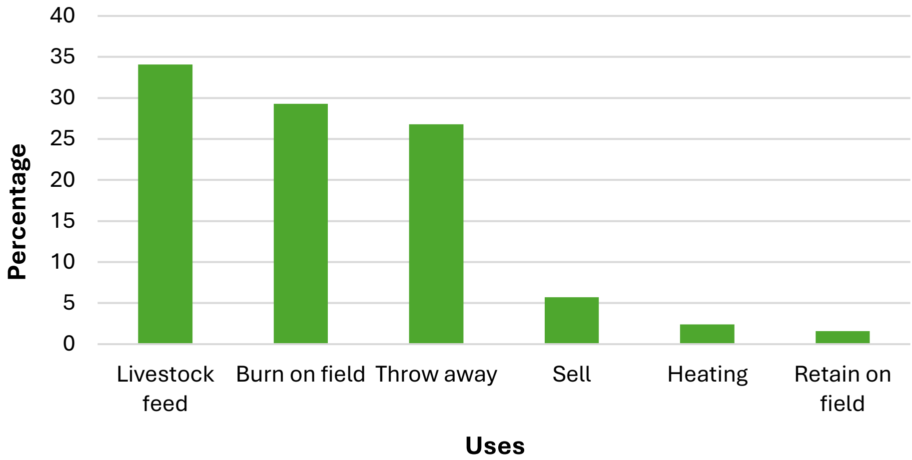

Figure 5.3. Uses of rice straw by farmers

As demonstrated in Figure 4, a significant proportion of farmers utilize rice husks for energy purposes, with a considerable number opting to sell it and a small percentage choosing to burn it.

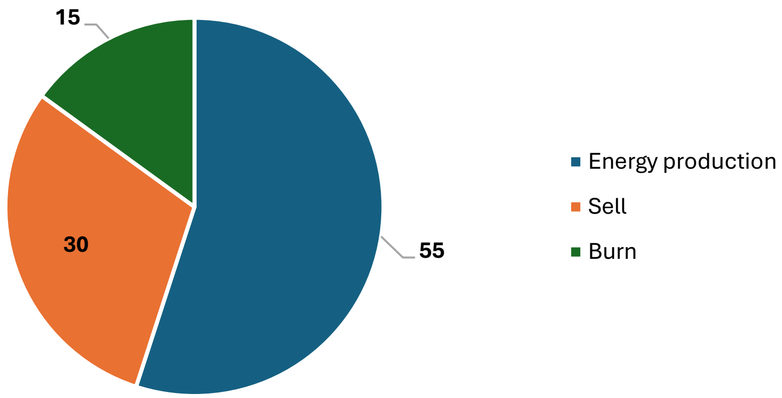

Figure 5.4. Rice husk utilization (%)

This tendency is consistent with the findings reported by Sekifuji & Tateda (2019), who observed that while most farmers in Japan employ rice husks for energy, a notable percentage resort to burning them. The predominance of rice husks usage as an energy source, coupled with its commercialization by farmers, signifies a higher potential for its adoption in energy valorization when compared to rice straw.

5.3.3. Cooking and heating energy for rice farmers

Figure 5.5 presents the cooking energy sources used by rice farmers in our sample. The majority rely on firewood and charcoal, with only about one-fifth using rice straw, while biogas is the least utilized energy source. This indicates a prevalent dependence on unclean and unsustainable energy sources, despite the significant potential for energy valorization of rice by-products. This is in line with IEA (2019) and Bappah et al. (2024), who reported that firewood and charcoal dominated the energy used for cooking in the country.

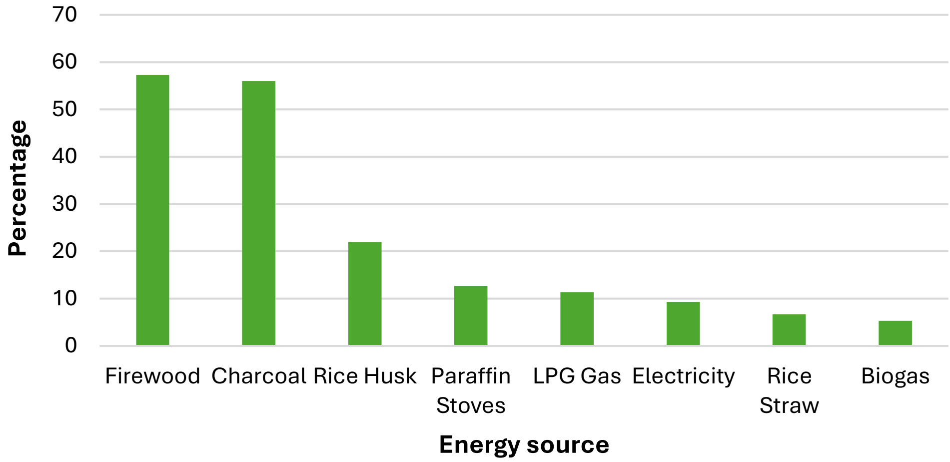

Figure 5.5. Rice farmers' source of energy for cooking

Figure 5.6 illustrates the heating energy sources utilized by rice farmers. The analysis reveals that approximately 60% of farmers employ firewood as a primary heating source, followed by 25% who utilize charcoal. Notably, 18% of farmers depend on rice husks as a heating fuel, while LPG gas is the least commonly used energy source. The pervasive use of charcoal and firewood in rural Nigeria has also been documented in the studies conducted by Ben-Iwo et al. (2016) and Bappah et al. (2024). Similarly, the same energy sources were reported as the major cooking fuels in Uganda and Afghanistan (Fahimi & Upham, 2018; Florkowski & Neupane, 2023). The high reliance on firewood and charcoal for both cooking and heating represents an unsustainable practice that contributes to deforestation and environmental degradation.

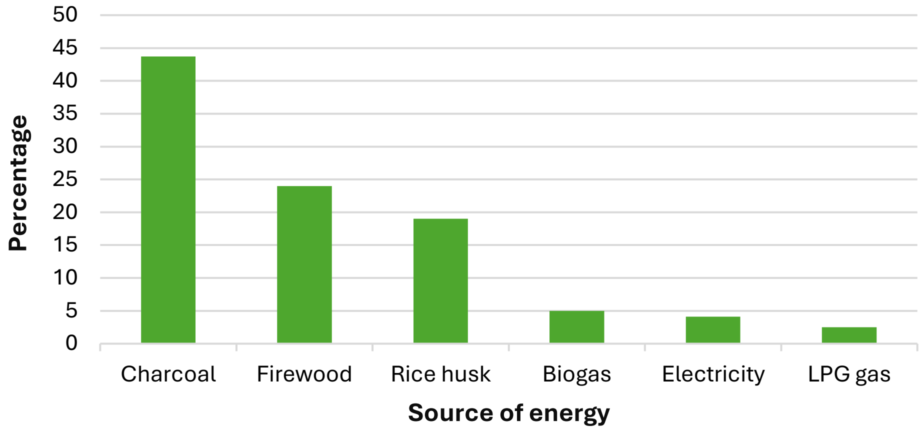

Figure 5.6. Rice farmers' source of energy for heating

5.3.4. Awareness and willingness of energy valorization of rice by-products

The bivariate probit regression results (Table 5.2) identify the factors influencing i. awareness and ii. willingness to adopt energy valorization practices for rice by-products. Regarding the demographic characteristics, a negative and statistically significant coefficient suggests that older farmers are less likely to be aware of energy valorization practices, which may be due to their limited exposure to information on modern technologies. Conversely, the positive and significant coefficient in the willingness model indicates that older farmers are more willing to adopt energy valorization practices, which may stem from their desire to ensure energy reliability and reduce dependence on traditional sources. The positive and significant coefficient in the model suggests that education enhances awareness. Educated farmers are more likely to access information and understand the potential benefits of energy valorization. Conversely, a negative and significant effect suggests that while education increases awareness, it may also highlight the costs or complexities of adoption, potentially reducing willingness. This positive effect of education on energy valorization awareness is also reported by Ajiboye et al. (2019).

A positive and significant effect of household size implies that larger households tend to be more aware. This could be because larger households face greater energy demands, motivating them to explore alternative energy solutions, on the other hand, negative and marginally significant coefficients suggest that larger households may face financial or logistical challenges, hindering their willingness to adopt. Ding et al. (2023) reported the effect of household size on willingness to adopt clean energy in China and highlighted constraints due to a lack of capital to invest. Regarding farm characteristics, a negative and significant effect of farm size implies that larger farm size discourages willingness, possibly because these farmers allocate by-products to other uses like soil enrichment. Lombardi & Berni (2021) reported that small size farms are more likely to adopt photovoltaic clean energy in Italy.

Table 5.2. Awareness and willingness to energy valorization of rice by-products

Variable	Awareness (Model 1)			Willingness to adopt (Model 2)		
	Coefficient	Std. Err.	p-value	Coefficient	Std. Err.	p-value
Socio-demographic characteristics						
Gender	0.001	0.744	0.999	0.560	0.610	0.359
Age	-0.089	0.369	***0.015***	0.072	0.027	***0.009***
Marital status	-0.157	0.389	0.686	-0.637	0.405	0.116
Education	0.301	0.076	***0.000***	-0.185	0.061	***0.003***
Household size	0.094	0.037	***0.012***	-0.057	0.030	***0.056***
Farming experience	0.004	0.021	0.836	0.001	0.023	0.958
Farm characteristics						
Total farm size	-0.048	0.069	***0.044***	-0.216	0.104	***0.039***
Land under rice cultivation	0.264	0.148	***0.075***	0.176	0.145	0.225
Livestock ownership	-1.224	0.364	***0.001***	0.098	0.307	0.749
Production system	0.545	0.305	***0.080***	0.545	0.330	***0.099***
Harvesting method	-0.703	0.727	0.333	-0.616	0.707	0.383
Rice processing	1.078	0.423	***0.011***	-1.245	0.351	***0.000***
Energy sources						

Firewood	-0.847	0.373	***0.023***	-0.989	0.359	***0.009***
Electricity	0.077	0.481	0.871	1.143	0.842	0.175
LPG	0.110	0.424	0.796	0.318	0.552	0.563
Constant	1.840	1.404	0.329	1.840	1.220	0.131
Wald chi2(32)	65.21					
Prob > chi2	0.000					

The negative and significant coefficient of livestock ownership suggests that farmers with livestock are less likely to be aware of rice by-products use for energy valorization. This may be because such farmers use rice by-products as animal feed, reducing their interest in alternative uses like energy valorization, as reported in the case of Indonesia and Bangladesh (Wadarni et al., 2021; Uddin & Fatema, 2016). Farmers involved in rice processing are more aware. This is likely due to the production of by-products such as rice husk and their potential utilization. While processors are more aware, they seem, according to our model results are not willing to adopt valorization practices due to competing priorities or higher perceived costs. Kaniapan et al. (2022) reported the effect of rice farm scale and operation on willing to adopt clean energy because techno-economic consideration of rice residues for energy argumentation.

Regarding the effect of energy sources used, a negative and significant effect of firewood use indicates that reliance on firewood as an energy source reduces awareness of the use of rice by-products. These farmers may be less motivated to seek alternatives because firewood is readily available. Similarly, a negative and significant coefficient indicates that dependence on firewood reduces the willingness to use the by-products. This is consistent with the idea that accessible and familiar sources of energy discourage change (Kwofie & Ngadi, 2019).

5.4. Conclusion and policy implications

This study investigates rice farmers' awareness and willingness to adopt energy valorization practices for rice by-products in Nigeria. The findings reveal significant variability in the utilization of rice straw and husk, with a substantial proportion of farmers using these by-products for non-energy purposes, such as animal feed and field burning. While many farmers are aware of energy valorization practices, slightly less than half of them express a willingness to adopt them, indicating gaps in understanding and potential barriers to adoption. The high reliance on firewood and charcoal for cooking and heating further underscores the unsustainable energy practices prevalent among rice-farming households, contributing to environmental degradation. Additionally, the bivariate probit regression results reveal that older farmers are less aware of energy valorization but demonstrate a higher willingness to adopt these practices, motivated by a need for reliable energy. Targeted awareness campaigns emphasizing the practical benefits of energy valorization for older farmers can address this gap. Education significantly improves awareness but may highlight adoption challenges, such as costs and complexities, potentially reducing willingness. Leveraging extension services and farmer cooperatives to provide simplified, actionable information can mitigate these barriers. Larger households, driven by greater energy demands, tend to be more aware but face financial and logistical challenges in adoption to handle the high volume of their generated residues. Offering financial incentives such as subsidies or grants can help them overcome these obstacles.

Farm characteristics also play a role. Larger farm sizes discourage adoption, as by-products are often allocated to other uses, such as soil enrichment. Technologies that balance these dual purposes can enhance adoption rates. Farmers with livestock prioritize rice by-products for animal feed, reducing their interest in energy valorization. Developing systems that enable by-products to serve both purposes, such as densification or fermentation and anaerobic digestion, which processes agricultural residues into bioethanol and biogas for energy, with protein-rich by-products repurposed as animal feed, can address this issue. Rice processors, while more aware of energy valorization practices, may face competing priorities or perceived costs that limit their willingness to adopt. Providing training and financial support for processors can position them as catalysts for broader adoption. Finally, reliance on firewood diminishes both awareness and willingness to adopt alternative energy solutions. Promoting cleaner alternatives like solid biofuels, biogas and biochar, alongside investments in collection and processing infrastructure, can drive adoption.

To align energy valorization practices with Nigeria's renewable energy goals, comprehensive awareness campaigns, infrastructure investments, and policy integration are crucial. By addressing these findings with targeted strategies, the adoption of sustainable energy solutions among rice farmers can be significantly advanced, contributing to environmental preservation and economic resilience.

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Author Contributions

All authors contributed to the design and conception of the study. Sylvia Ukamaka Echefu: Data collection, Methodology, Data Analysis, First draft, Writing - review & editing. Musa Bappah: Data collection, Methodology, Data Analysis, First draft, Writing - review & editing. Tatiana Alexiou Ivanova: Methodology, Supervision, Funding acquisition, Resources, Writing - review & editing. Mustapha Yakubu Madaki: Methodology, Data Analysis, First draft, Writing - review & editing. Williams Nkomoki: Methodology, Data Analysis, Writing - review & editing. Ayat Ullah: Data Analysis, Writing - review & editing. Mirka Bavorova: Supervision, Writing - review & editing.

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CHAPTER 6 Energy characterization of selected Nigerian agricultural by-products

Adopted from: Bappah M., Alexiou Ivanova T., Bradna J., Chaloupková V., Velebil J., Llorente M.F. Energy characterization of potential Nigerian agricultural by-products. Submitted to *Fuel*.

Abstract

Rice, corn, and peanuts are among the major crops produced in Nigeria, from which rice husks, corn cobs, and peanut shells are, respectively, generated as by-products. They are mostly discarded or burned in the open, releasing unwanted gases, thereby affecting human health and the environment. Proper handling of these by-products will be a favorable way of protecting the environment and can lead to the provision of energy sources that are eco-friendly, thereby reducing the impact of polluting fuels. Some of the challenges associated with the utilization of non-woody biomass, like husks, straws, and shells, via combustion, are low calorific value, high ash content, low bulk density, and high moisture absorption ability. Energy characteristics of these by-products, including calorific value, ash content, ash-forming elements, and ash melting behavior, were investigated for combustion purposes. Corn cobs and peanut shells were discovered to have high calorific values and low ash contents. Low nitrogen and sulfur contents of all studied by-products reveal their lower tendency to emit associated oxides during combustion. The ash of rice husks presents a low sintering tendency at higher combustion temperatures of over 1450 ºC, whereas the ash of corn cobs and peanut shells are more likely to sinter at certain points of the combustion process. Torrefaction was discovered to improve the energy properties of all the by-products. Over 5 million tons of these by-products are estimated to be generated annually in Nigeria, from which 21.40 TWh of energy can be generated.

Keywords: corn cobs; maize stover; peanut shells; groundnut pods; rice husk; energy potential; biomass energy; solid biofuel properties; torrefaction

6.1. Introduction

Considering global concern towards scarcity of resources resulting from rising population, coupled with increased agricultural activities and energy requirements, aiming at providing the basic needs of the teeming population, a lot of waste is produced, causing negative impacts on humans and the environment. This increasing global population, which is expected to reach 9 billion by the year 2050, is bringing about an increase in energy demand as well as fossil fuel consumption (Perea-Moreno et al., 2019). Utilization of other renewable alternative sources of energy is the only option for overcoming the pressure on fossil fuels and reducing its effects on humans and the environment (FitzHerbert, 1999). Agricultural by-products obtained from different stages of agricultural activities, ranging from harvesting to final processing are promising biomass that can be considered for energy generation, which will subsequently lead to the reduction of carbon dioxide (CO_2) emissions to the atmosphere [3, 4]. Biomass is obtained both at farm and industrial levels, depending on technology, resource availability, geography, economy, and biodiversity, with an estimated potential of generating 3000 TWh of electricity, thereby saving 1.3 Bt of CO_2 equivalent (Antar et al., 2021; Gielen et al., 2019).

Corn, wheat, and rice are the major staple foods from which over 50% of the daily global calorie intake is derived, and billions of people depend for their survival (Awika, 2011). The global annual production of corn and rice was estimated to be over one billion metric tons (Erenstein et al., 2022) and 529 million tons (FAO, 2022) respectively. The cobs of the corn comprise about 18% of the fruit/seed mass (Blandino et al., 2016), and 20% of the total shoot residues (Santolini et al., 2022), while 43% of the total rice production is estimated to be the husks and the straw (Adeoye et al., 2011). Rice husks, which are considered to be one of the most abundant wastes, generated from the agricultural industry in rice-producing countries (Kordi et al., 2024; Singh Karam et al., 2022) constitutes about 20% of the weight of paddy rice (Dunnigan et al., 2018; Singh Karam et al., 2022). Nigeria is ranked the second largest producer of corn in Africa, with an estimated annual production of about 13 million tons (FAOSTAT, 2022; PwC, 2021), and the leading producer of rice at an estimated rate of 8.5 million tons (DERFTDAN, 2023; FAOSTAT, 2022), which is expected to double by 2030 (FMARD, 2020). Rice and corn are common agricultural produce in almost all geopolitical zones of Nigeria, with the exception of South-south (Chiaka et al., 2022). North-west accounts for 72% of the country's rice production (DERFTDAN, 2023). Ten states of the country, which are considered the top corn producers (Bauchi, Borno, Niger, Kaduna, Plateau, Katsina, Gombe, Kogi, Oyo and Taraba), account for 64% of its corn production (PwC, 2021). Out of these ten states, 4 are from the North-east, 2 from North-west, 3 from North-central and 1 from South-west.

With an estimated global annual production of 53.6 million tons (FAOSTAT, 2022), peanut is considered an important cash crop, especially in Africa and some Asian countries (A. James & Yadav, 2021; Maiti & Wesche-Ebeling, 2002). Peanut shells are the major by-product obtained from peanuts, consisting of 20-30% of the total crop weight (Adeoye et al., 2011). As a leading producer of peanuts in Africa and the third in the whole world, after China and India, with an annual production of 4.28 million tons (FAOSTAT, 2022), Nigeria is generating a huge amount of pods, whose energy utilization has not been explored. Peanut is mostly produced across the northern states of the country (Hakeem A Ajeigbe, Farid Waliyar, Candidus A Echekwu, Ayuba Kunihya, Babu N Motagi, 2015).

Country's remarkable contribution to corn and rice production left it with unquantified corn cobs and rice husks, which are mostly disposed of in landfills and drainage channels or inappropriately handled, thereby causing a negative impact on the environment. Both corn cobs, rice husks, and peanut shells are usually discarded or burned, without deriving any benefit, especially in rural areas.

Some of the challenges associated with (non-woody) biomass utilization for combustion purposes are low energy qualities, such as low heating value, low bulk density, high moisture absorption ability (D. Chen et al., 2015; Niu et al., 2019) and high content of ash (Niu et al., 2019). Thermal treatment and densification were found to address these challenges by improving the heating value, reducing the moisture absorption as well as improving the bulk density (W. Chen et al., 2019; Irawan et al., 2017; Niu et al., 2019). Appropriate treatment temperature depends on the biomass and its respective properties for better quality improvement.

Nonwoody biomass, such as stalks, straws, and grasses are characterized by a high content of alkaline (Ge et al., 2022; Haykiri-Acma et al., 2010; Llorente & García, 2005) and alkaline earth elements (Ge et al., 2022; Haykiri-Acma et al., 2010) compared to their woody counterparts, leading to a higher content of ash (Ge et al., 2022; Haykiri-Acma et al., 2010; Llorente & García, 2005), with low ash melting temperature (Haykiri-Acma et al., 2010; Llorente & García, 2005). Over 475 million tons of ash is estimated to be generated annually from the combustion of 7 billion tons of biomass with an ash content of 6.7% (Dogar et al., 2020; Munawar et al., 2021; Vassilev et al., 2010). The component composition of the biomass ash (Ca, K, Na, and Mg) (Haykiri-Acma et al., 2010), which increases the tendency of ash to melt at low temperatures (Fan et al., 2020), can be related to its sintering behavior (Haykiri-Acma et al., 2010). This sintering affects the heat exchanger by forming ash deposits, thereby reducing its efficiency, increasing cleaning costs and time, and causing wear and tear (Baxter et al., 1998).

With the current fuel subsidy removal (Evans et al., 2023; Ozili & Obiora, 2023) and vandalism of electricity transmission lines (Adeyinka Victor et al., 2024), which makes basic necessities, including energy sources, unaffordable to the common citizen (Evans et al., 2023; Ozili & Obiora, 2023), the provision of alternative energy sources, especially from biomass, which is considered waste, will help in managing the environmental impacts and providing a clean and eco-friendly source of energy that can be accessible and affordable to all citizens and, at the same time, reduces the impact of firewood utilization on forest and forest resources. The estimated annual firewood consumption in Nigeria was reported to be over 50 million metric tons, which exceeds possible forest regeneration of the country (Adamu et al., 2020). This can be the main cause of forest thinning in the country and one of the contributing factors to climate challenges.

Even though the energy properties of these selected agricultural by-products from different parts of the world were studied (Biagini et al., 2015; Kumari & Gupta, 2023), research on the Nigerian by-products is very scanty and their energy potential is not well explored. Some of the researches conducted on Nigerian by-products focus on electricity generation (Y. S. Mohammed et al., 2020), biogas production, with very few on solid biofuel production. This research, therefore, focuses on determining the energy characteristics of agricultural by-products obtained from some of the major Nigerian crops (corn cobs, rice husks, and peanut shells) for combustion purposes. This combustion can be directly as fuel, co-firing or conversion into other forms of energy like electricity.

6.2. Methodology

Samples of three different agricultural by-products (corn cobs, peanut shells, and rice husks) were separately collected from different farms and processing facilities in Nigeria. The samples collected of each by-product were mixed and homogenized, from which the representative samples were obtained and used for analysis.

6.2.1. Sample Preparation

Analytical samples were prepared by crushing the by-products through a 0.5 mm screen, in accordance with the provisions of ISO 14780:2017/AMD 1:2019, using Foss Cyclotec 1093 laboratory mill.

6.2.2. Proximate and Ultimate Analysis

Moisture content (MC), ash content (AC) and volatile matter (VM) were measured using a thermogravimetric analyzer (Leco TGA-701) using ISO 181s34-3:2023, ISO 18122:2022, and 18123:2023 standards, respectively. Fixed carbon (FC) in dry basis percentage was calculated using equation (6.1).

$$FC = 100 - (AC + VM) \tag{6.1}$$

Gross calorific value (GCV) was measured using a PARR 6400 automatic isoperibol calorimeter, and Net calorific (NCV) value was calculated using equation (6.2) as prescribed by ISO 18125:2017.

$$Q_{p.net} = Q_{v.gr} - 212.2 \times w(H)_d - 0.8 \times [w(O)_d + w(N)_d] \tag{6.2}$$

Where $Q_{p.net}$ — net calorific value ($J.g^{-1}$); $Q_{v.gr}$ — gross calorific value of a biofuel sample ($J.g^{-1}$); $w(H)_d$ — hydrogen content in the dry basis of the biofuel sample (%);

$w(O)_d$ — oxygen content in the dry basis of the biofuel sample (%); $w(N)_d$ — nitrogen content in the dry basis of the biofuel sample (%).

LecoSpec-macro sample CHN elemental analyzer was used to measure the composition of carbon (C), hydrogen (H), and nitrogen (N) on the dry basis of the biomass samples, in accordance with the provisions of ISO 16948 standard. An aqueous solution of the biomass sample obtained from a bomb calorimeter during calorific value determination was used in determining the content of chlorine (Cl) and sulfur (S), as prescribed in ISO 16994, using 883 Basic IC Plus, Methrom chromatography. The oxygen (O) content was then calculated using equation (6.3):

$$O = 100 - (C + H + N + S + Ash) \quad (6.3)$$

Where O — mass percentages of oxygen (%); C — mass percentages of carbon (%); H — mass percentages of hydrogen (%); N — mass percentages of nitrogen (%); S — mass percentages of sulfur (%); Ash — mass percentages of ash content (%)

6.2.3. Ash forming elements

The composition of the elements in the ashes of the test samples was determined by the ash microwave digestion and Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) method, which identifies and quantifies the elements that are present in the ash with emission spectra using Thermo-Jarrell Ash. The content of chlorine in the ash was determined according to ASTM D2361- 66 using the indirect Volhard process (Chaloupková et al., 2021).

6.2.4. Ash fusion test

This test was carried out to determine the ash melting behavior of the agricultural by-products to ascertain their possible utilization for solid biofuel production and subsequent determination of combustion-associated problems. The test was carried out using a Hesse instrument HT15 optical heating microscope with an automated analyzer, in accordance with the provisions of ISO 21404. The behavior was determined from the changes occurring in the shape and surface area of a 6mm diameter by 6mm height ash pellet (Link et al., 2018). Shrinkage, deformation, hemisphere, and flow temperatures were the characteristic temperatures considered during the process.

6.2.5. Ash sintering

The sintering and fusion prediction was determined using equation (6.4) by determining the ratio of alkaline earth oxides to alkaline oxides as provided by Fernandez Llorente and Carrasco Garcia. In general, it could be said that biomasses with $(CaO+MgO)/(K_2O+Na_2O)$ values higher than 2 should not present risk of sintering. This method is mentioned to be less reliable in comparison with the fusion test (Llorente & García, 2005).

$$I = CaO + MgO/K_2O + Na_2O \quad (6.4)$$

6.2.6. Thermal treatment

Thermal treatment of the biomass for upgrading the fuel quality was carried out through the removal of volatile organic compounds and water (Pradhan et al., 2018) using Thermogravimetric analyzer LECO 701 at four different temperatures of 200, 300, 400, and 500 °C. Properties of the biochar produced, including calorific value, moisture content, ash content and volatile matter, were measured to determine the impact of the treatment.

6.2.7. Energy yield

The annual energy yields (EY) of the agricultural by-products were determined using equation (6.5), by multiplying the annual biomass yields with their respective energy values (Akhmedov et al., 2019; Karaca, 2015).

$$EY = W_T \times NCV \quad (6.5)$$

Where EY – the energy yield of the by-product (J); W_T – the quantity of the by-product (T); NCV – the net calorific value of the by-product ($MJ.kg^{-1}$).

6.3. Results and discussion

6.3.1. Proximate and Ultimate Analysis

All samples were discovered to have low moisture content, which is optimum for different forms of solid biofuel production. This low moisture may result from the weather conditions of the environment during harvesting and processing. The energy and time required for drying the biomass will, therefore, be reduced, thereby causing a reduction in the cost of the final biofuel. High temperature and low humidity will reduce the biomass moisture drastically within a short time when exposed to the condition (Niu et al., 2019). Even though corn cobs and peanut shells have a low ash content of 1.80 and 3.40, respectively, peanut shells are not optimum for high-quality briquette or pellet production, but they are good for non-woody pellets and briquette production (ISO 17225-2, 2015; ISO 17225-3, 2014; ISO 17225-6, 2014; ISO 17225-7, 2014). These ash contents are similar to that of wood and woody biomass (Vassilev et al., 2017), indicating the possibility of their utilization as a substitute without thinking of additional burden for ash management. The ash content of rice husks (Table 6.1) is similar to what was reported in relevant studies [33, 53, 54]. It was discovered to be 11 times higher than that of corn cobs and 6 times higher than peanut shell ash. The high ash content of biomass lowers its energy yield and also increases the cost of boiler maintenance and ash management (Khan et al., 2009; Kumar et al., 2013; Munawar et al., 2021).

Table 6.1. Proximate and ultimate analysis

Parameter	**Symbol**	**Unit**	**Corn cobs**	**Peanut shells**	**Rice husks**
Moisture content	MC	%w.b.	7.10	7.60	7.40
Ash content	AC	%d.b.	1.80	3.40	20.9
Volatile matter	VM	%d.b.	80.50	72.20	53.8
Fixed carbon	FC	%d.b.	10.60	16.80	17.90
Carbon content	C	%d.b.	47.90	49.70	38.30
Hydrogen content	H	%d.b.	5.90	5.80	4.90
Nitrogen content	N	%d.b.	0.41	1.38	0.42
Sulphur content	S	%d.b.	0.02	0.04	0.03
Oxygen content	O	%d.b.	43.81	39.67	35.44
Gross Calorific Value (d.b)	GCV	$MJ.kg^{-1}$	18.77	19.94	15.25
Net Calorific Value (d.b.)	NCV	$MJ.kg^{-1}$	17.48	18.68	14.18

w.b. – wet basis; d.b. – dry basis

Volatile matter which determines the ignition and flammability of the biomass (Sadiku et al., 2016) was discovered to be higher in corn cobs and peanut shells (80.5% and 72.2%, respectively) than in rice husks (Table 6.1). More efficient combustion, with higher heat generation, is achieved on biomass with high volatile matter (Ivanova et al., 2018). Rice husks have significantly lower volatile matter than corn cobs and peanut shells, indicating that corn cobs and peanut shells will be easier to ignite and will produce more heat during combustion than rice husks. In order to ensure the complete combustion of a fuel with high volatile matter, a high amount of air is required to avoid dark smoke and soot deposits on the boiler surface (Patel, 2012; Sadiku et al., 2016). Volatile matter of 70% to 80% was reported on different biomass, including woody ones (Ivanova et al., 2018). Lower values of volatile matter were reported for corn cobs and peanut shells and higher for rice husks by Kumar and Gupta (Kumari & Gupta, 2023) as 74.09, 69.22 and 64.21, respectively. Corn cobs and peanut shells can, therefore, be considered as best materials for combustion, which can be compared with fuelwood, judging by the content of their volatile matters.

The fraction of the biomass that remains after subjecting it to higher temperatures and releasing moisture and volatiles is considered to be its fixed carbon (Kumari & Gupta, 2023). Heat generation during combustion depends on the fixed carbon content of the biomass material. Rice husk was discovered to have a higher fixed carbon content of 17.90%, which is significantly higher than that of corn cobs and slightly higher than that of peanut shells (Table 6.1). Fixed carbon content of biomass plays a role in energy recovery from that biomass (Jain et al., 2016). More energy is therefore expected to be recovered from rice husk than corn cobs, which can be attributed to its slow combustion. Kumari and Gupta reported fixed carbon of 14%-16%, with peanut shells having the highest (Kumari & Gupta, 2023). With the exception of corn cobs, whose fixed carbon appears to be low, the fixed carbon obtained in this study is comparatively higher than the values reported (Kumari & Gupta, 2023).

Carbon content is considered as the major parameter for determining the heating value of the biomass (Sadiku et al., 2016). Biomass with higher carbon contents is expected to have a higher calorific value, as observed in Table 1. Corn cobs and peanut shells have higher contents of carbon than rice husks. Peanut shells with the highest carbon content appear to have higher calorific value, while rice husks, whose carbon content was the least has lower calorific value than corn cobs and peanut shells. The calorific value of corn cobs and peanut shells is within the specification of the best woody briquettes and pellets [48, 51], while that of rice husks can only be considered enough for non-woody pellets or briquettes specification (ISO 17225-6, 2014; ISO 17225-7, 2014). The gross calorific value of peanut shells, corn cobs and rice husks were reported to be 16.8 $MJ.kg^{-1}$, 15.6 $MJ.kg^{-1}$ and 14 $MJ.kg^{-1}$ respectively (Kumari & Gupta, 2023), which are significantly lower than the values obtained in this research. Judging by the CV, corn cobs and peanut shells can serve as good substitutes for fuelwood and can be used as feedstock for solid biofuel production. The biofuel produced from these by-products can conveniently be used in place of fuelwood and can serve the same purpose of heating and cooking, which is the main challenge in developing countries like Nigeria.

Corn cobs and rice husks were discovered to have low nitrogen content, whereas peanut shells have relatively higher (Table 6.1). The nitrogen content of peanut shells is 227% higher than that of corn cobs and rice husks. The nitrogen content of the best-graded woody pellets should not be more than 0.3% (ISO 17225-2, 2015). All studied biomasses have similar or less nitrogen than coal (Gopinathan et al., 2022). While corn cobs and rice husks have even met the required nitrogen limit for the grade A2 woody pellets (which is the second-best solid biofuel class), peanut shells fulfilled the limit for the grade A non-woody pellets (ISO 17225-2, 2015; ISO 17225-6, 2014). All the by-products have a low content of sulfur, which is lower than that of coal [57, 58] and within the limit for the grade A wood pellets (ISO 17225-2, 2015).

Similar results on the proximate and ultimate analysis of rice husks were reported by Haykiri-Acma et al., though this study was found to have slightly higher calorific value and fixed carbon, and less oxygen and nitrogen content than what was reported (Haykiri-Acma et al., 2010). Less ash content (16.5%) was reported by Vassilev et al. (Vassilev et al., 2010), which may result from chemical and soil composition. Zero S content was also reported by Yaman (Haykiri-Acma et al., 2010).

6.3.2. Ash forming elements

The chemical composition of the ash was measured in the form of oxides of the chemical elements, and the result is presented in Table 6.2. Si, Al, Fe, Ca, Mg, Mn, Na, K, P, S, and Cl are the solid fuels main ash-forming elements [44, 55]. High content of Si and K lowers the ash melting temperature of the fuel ash, whereas Ca and Mg raise the melting temperature (Khan et al., 2009). S, which SO_X formation depends on, plays an important role in corrosion and deposit formation. At temperatures above 500 ^{O}C, the presence of Cl in the fuel contributes to inducing corrosion to the boilers (Khan et al., 2009; Munawar et al., 2021).

The dominant elements for corn cobs and peanut shell ashes are K_2O and SiO_2, whereas rice husk ash is dominated by SiO_2, with very low K_2O content. K_2O is one of the dominant elements of biomass ash (Haykiri-Acma et al., 2010; Reinmöller et al., 2019), resulting from K intake from the fertilizer that is applied during the growing process and the mineral intake (Reinmöller et al., 2019). Rice husk ash has a comparatively lower content of CaO (0.57%), with peanut shells having 6.4%, which is over 2 times higher than that of corn cobs ash. There is a great variation in the K_2O content of the by-product ashes, with corn cobs having the highest (40.6%) and peanut shells and rice husks having 30.5% and 0.83%, respectively. The content of MgO and Na_2O in peanut shell ash is almost two times higher than that of corn cobs ash, while that of rice husk ash is very low. Rice husk ash has a low content of both alkaline metal and alkaline earth metals but a high content of acidic oxides due to the higher content of SiO_2 (92%). A similar amount of SiO_2 was reported for rice husks by other studies (Haykiri-Acma et al., 2010; Kumar et al., 2013; Madhiyanon et al., 2009).

Table 6.2. Chemical composition of corn cobs, peanut shells and rice husks ashes

Element	Corn cobs (%)	Peanut shells (%)	Rice husks (%)
Al_2O_3	0.55	2.64	0.73
BaO	0.026	0.092	0.015
CaO	2.8	6.4	0.57
Fe_2O_3	0.96	0.87	0.94
K_2O	40.6	30.5	0.83
MgO	2.00	4.83	0.34
Mn_2O_3	0.08	0.10	0.11
Na_2O	0.257	0.486	0.052
P_2O_5	4.09	4.09	0.39
SO_3	2.48	2.00	0.23
SiO_2	23.5	18.6	92
SrO	0.019	0.041	0.003
TiO_2	0.038	0.200	0.051
ZnO	0.213	0.061	0.035
Cl	0.16	0.01	0.01

6.3.3. Ash fusion

The patterns of the ash melting are presented in Figure 6.1. All four ash melting phases were observed in the case of peanut shells and corn cob ashes. The shrinkage, deformation, hemisphere and flow phases of the peanut shells ash and corn cobs ash are presented in Figure 6.1 a,b,c,d, and e,f,g,h, respectively. Shrinkage is the first phase of the ash melting process, where moisture and other volatiles are burned out of the ash pellet, thereby reducing its surface area (Figure 6.1 a, e and i). As the temperature increases, the ash pellets begin to soften, and their structure begins to alter, representing deformation of the pellet (Figure 6.1 b and f). Further heating reduces the height of the pellets and makes them hemispheric shape through surface melting (Figure 6.1 c and g), which later eventually flow (Figure 6.1 d and h). The only sign of shrinkage was observed in the case of rice husk ash (Figure 6.1 i - l).

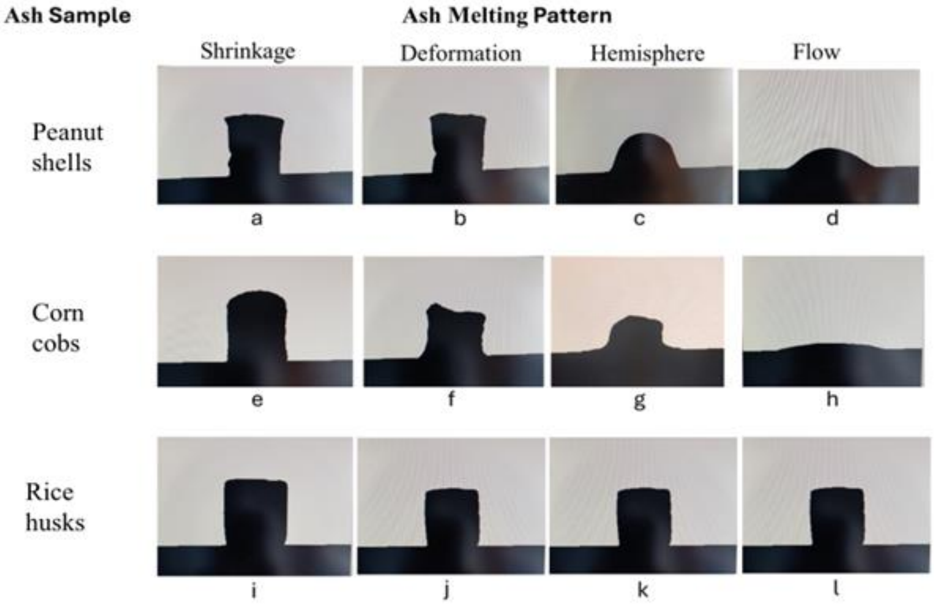

Figure 6.1. Ash melting behavior

The result of the fusion test is presented in Table 6.3 with all the changes that occur during the combustion of the ash pellets. A sign of shrinkage was noticed when the area of the ash pellet started to decrease by less than 5% of its original size, which was observed at 1,090 ºC, 720 ºC, and 850 ºC for the peanut shells, corn cobs, and rice husks, respectively. As corn cobs and peanut shell ashes present a sign of deformation at 1,020 ºC and 1,210 ºC, respectively, rice husk ash did not indicate any sign of deformation up to the operational temperature limit (1,450 ºC), meaning its deformation temperature is beyond that limit. A deformation temperature above 1,000 ºC was observed for all the biomass ashes. Despite its high ash content, rice husk ash has much less tendency to deform at higher combustion temperatures compared to corn cob ash and peanut shell ash, which will have more resistance to melting at higher combustion temperatures of around 1,000 ºC. All the ashes were discovered to have high flow temperatures close to the operational temperature limit, with rice husk ash having the highest (the best).

Table 6.3. Ash fusion temperatures

Sample	**ST** (°C)	**DT** (°C)	**HT** (°C)	**FT** (°C)
Corn cobs	720	1,020	1,170	1,240
Peanut shells	1,090	1,210	1,290	1,320
Rice husks	850	> 1,450	> 1,450	> 1,450

ST-Shrinkage temperature; DT-Deformation temperature; HT-Hemisphere temperature; FT-Flow temperature

Sintering starts between shrinkage and deformation temperatures, and it reaches its peak between deformation and hemisphere temperatures (Ge et al., 2022). No sintering is therefore expected to occur on combusting rice husk at an elevated temperature of 1,450 °C or more. Peanut shells and corn cobs can reach 1,100 °C and 850 °C, respectively, without sintering tendencies. Based on the deformation temperature, all the by-products have less tendency to sinter during combustion at low temperatures. Their deformation is similar to what was reported by Llorente et al., (Llorente & García, 2005) on woody biomass, with a deformation temperature just above 1,100 °C.

6.3.4. Ash sintering

Based on the ratio of alkaline earth oxides to alkaline oxides, peanut shells have a higher sintering index compared to corn cobs. The index will not be applicable on rice husks due to its high SiO_2 content, which is greater than 90%, thereby making its sintering temperature high (Llorente & García, 2005). Slag formation from the combustion of biomass obtained from annual crops usually results from the high alkaline content of the biomass (Haykiri-Acma et al., 2010).

For the alkaline earth oxides to alkaline oxides ratio, biomasses with high alkaline earth to alkaline ratio are expected to have lower sintering tendencies than those with lower indexes. Again, confirming better behavior for rice husks.

Table 6.4. Ash sintering index

Sintering index	**Corn cobs**	**Peanut shells**	**Rice husks**
Alkaline metals / alkaline earth metals	0.117483	0.362422	NA

NA – not applicable

Peanut shells and rice husks have a low content of chlorine, which is the element promoting the formation of NaCl and KCl (Reinmöller et al., 2019), while corn cobs have relatively higher Cl content. Low melting phase formation from precipitation of alkaline metal silicates, mainly Na and K, is considered the main cause of sintering

(Llorente & García, 2005). Biomasses with high K_2O content are expected to have a higher tendency of slag formation during combustion (Reinmöller et al., 2019).

6.3.5. Thermal treatment

The result of the samples' treatment is presented in Table 6.5. Energy parameters of the torrefied biomass that were measured after the treatment are calorific value, ash content, volatile matter and moisture content. Fixed carbon was calculated from ash content and volatile matter, using equation 6.1. The moisture content of the treated biomass appears to have a direct variation with the treatment temperature. An increase in the treatment temperature causes a rise in the moisture content of all the by-products. This results from the decomposition of the biomass, where moisture is absorbed by dry material during the decomposition process (Niu et al., 2019).

Table 6.5. Characteristics of thermally treated biomass materials

Sample	**MC** (% w.b.)	**AC** (% d.b.)	**VC** (% d.b.)	**FC** (% d.b.)	**GCV d.b.** ($MJ.kg^{-1}$)
Corn cobs					
Treated (200 ºC)	0.27	2.02	80.53	17.45	17.74
Treated (300 ºC)	1.00	3.11	59.15	37.74	22.68
Treated (400 ºC)	1.81	5.69	31.50	62.81	27.40
Treated (500 ºC)	3.04	6.78	22.65	70.57	30.90
Peanut shells					
Treated (200 ºC)	0.11	3.76	65.10	31.14	20.54
Treated (300 ºC)	0.47	5.10	54.41	40.49	24.03
Treated (400 ºC)	1.32	8.72	23.00	68.28	27.96
Treated (500 ºC)	2.15	10.08	16.24	73.68	29.14
Rice husks					
Treated (200 ºC)	0.07	21.09	72.82	6.09	15.57
Treated (300 ºC)	0.54	25.91	59.31	14.78	16.74
Treated (400 ºC)	1.35	41.38	31.50	27.12	16.93
Treated (500 ºC)	2.47	46.68	22.65	30.67	16.59

As expected, the calorific value of all the by-products increases with increasing treatment temperature. This results from the breaking down of hemicellulose matter of the biomass and leaving behind cellulose and lignin, which are more energy dense. During thermal treatment, there used to be a loss of oxygen and hydrogen, thereby increasing the C/H and C/O ratios, leading to an increase in the calorific value. The content of the volatile matter was discovered to decrease with increasing treatment temperature. The ash content also increases as the treatment temperature is raised (Singh Karam et al., 2022), resulting from loss of volatile matter and some part of hemicellulose and cellulose matter, which have no ash.

treatment at 200 ºC indicates a little increase in the calorific value. As the temperature increased to 300 ºC, a significant rise in the calorific value was noticed in the case of corn cobs and peanut shells. For corn cobs, the calorific value increased by 20.83%, while that of peanut shells increased by 20.51% at 300 ºC treatment temperature. Even though the ash content of corn cobs and peanut shells also increases by 72.78% and 50%, respectively, they are still within the prescribed limit for graded non-woody pellets and briquettes. The highest calorific value was obtained on 500 ºC treated corn cobs and peanut shells with an increment of 64.62 and 46.14% from the original ones, respectively. As the calorific value increases, the ash content also increases by 276.67% and 196.47% respectively. Unlike corn cobs and peanut shells, the increase in calorific value on 300 ºC treated rice husks was only 9.77%, and 8,79% on 500 ºC, whereas the increment in the ash content was discovered to be 23.97% and 123.35%. Considering the impact it has on the heating value of biomass and the fact that it requires little external energy to achieve this improvement, torrefaction is recommended (Pirraglia et al., 2012) on biomass with less ash content.

6.3.6. Energy yield

Biomass potential

Considering the annual production of corn, peanut and rice in Nigeria and the percentage of respective by-products (corn cobs, peanut shells and rice husks) that are obtained from them, which can be acquired at negligible or no cost, the amount of by-products that can be generated from those crops are presented in Figure 6.2. Corn cobs, with the highest crop yield, have the highest by-product generation potential of about 46% of the combined by-products, while peanut shells have the least, with the potential of generating only 21% (out of three selected biomasses).

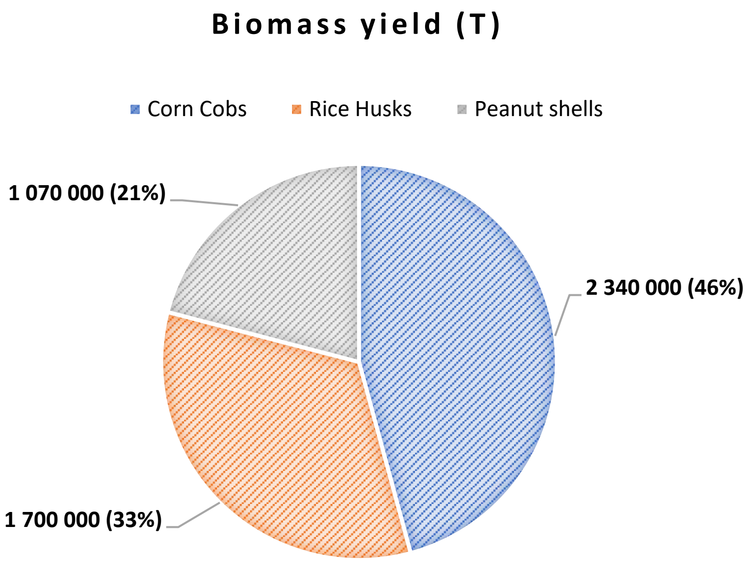

Figure 6.2. Annual biomass yield of the by-products

A total of 5.11 million tons of biomass can be generated annually from these three agricultural by-products throughout Nigeria. Allowing this quantity of by-products to end up as waste, mostly in the drainage channels, is creating and will continue to create many problems. Among these problems is the blocking of waterways, thereby causing floods within the nearby communities and contributing to breeding disease-causing vectors like mosquitoes.

Energy potential

The energy yield of the by-products was determined from their respective NCV and biomass yield. If well collected, handled and managed, the amount of energy that can be generated from each of these agricultural by-products is presented in Table 6.6.

Table 6.6. Annual energy yield of the by-products

Biomass	**EY (TJ)**	**EY (TWh)**
Corn Cobs	37,106.76	10.31
Rice Husks	21,806.91	6.06
Peanut shells	18,132.45	5.04
TOTAL	77,046.11	21.40

For Nigeria, with a total energy supply of 6,900,832 TJ (IRENA, 2022), these 3 agricultural by-products generated from some of the major Nigerian crops, can provide nearly 2% of the country's energy supply. Over 73% of the Nigerian energy supply is obtained from waste and traditional biomass (Bamgbopa et al., n.d.), which can be supplemented with modern biomass utilization. Household is the most energy-consuming sector in Nigeria, covering about 65% of the total country's energy usage, over 70% of which comes from traditional sources.

With an average per capita energy consumption of 2,548 kWh (Ritchie et al., 2022), corn cobs, peanut shells and rice husks generated as wastes from the common agricultural crops, can provide for the energy requirement of over 8,398,000 Nigerians. For individual by-products, corn cobs, which have the highest energy yield, can cover the energy demand of 4,046,310 people. Rice husks and peanut shells can provide for 2,378,335 and 1,978,021 people, respectively. Each of these by-products can cover the per capita energy demand of at least one state of the country.

6.4. Conclusion

Corn, rice and peanuts are among the major crops that are produced in Nigeria, whose by-products (corn cobs, rice husks, and peanut shells, respectively) are mostly discarded or burned in an open environment due to their lack of nutritional value for feeding animals. These by-products have great potential for energy, which can contribute to the energy mix of the country and reduce over-dependence on traditional fuels for cooking and heating, thereby saving the forest and the environment. The low content of moisture and ash and the high volatile matter content of peanut shells and corn cobs make them better materials that can be considered for solid biofuel production. Even though the ash content of rice husks is high, it does not contain harmful elements that will hinder its utilization as fertilizer on the farm. The low tendency of sintering observed from rice husk and the low ash content of corn cobs and peanut shells opens the possibility of mixing the by-products during fuel production to improve each other for a better combustion process. Torrefaction at 300 ^{o}C significantly improves the CV in the case of corn cobs and peanut shells. Though there is an increase in the ash content, it is still within the limit specified for non-woody pellets and briquettes. The energy potential of the by-products, which can serve the average energy demand of over 13 million Nigerians, will contribute to the country's energy mix and reduce the impact of polluting fuels, especially on women and children. This will help relevant government agencies and concerned organizations in exploring the potential of not only these by-products, but also other abandoned biomass that are available all over the country.

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Author Contributions

All authors contributed to the design and conception of the study. **Musa Bappah**: Data collection, Methodology, Data Analysis, First draft, Writing - review & editing. **Tatiana Alexiou Ivanova**: Methodology, Supervision, Funding acquisition, Resources, Writing - review & editing. **Jiří Bradna**: Methodology, Data Analysis, Writing - review & editing. **Veronika Chaloupková**: Data Analysis, Writing - review & editing**. Jan Velebil**: Data Analysis, Writing - review & editing., **Miguel Fernandez Llorente**: Resources, Supervision, Writing - review & editing

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CHAPTER 7 Biofuel production from selected Nigerian agricultural by-products and their thermo-mechanical properties

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Abstract
As an organic material, biomass is highly versatile in the renewable energy sector due to its ability to be transformed into all forms of fuel (solid, liquid and gas), depending on its composition and characterization. Its versatility, along with carbon neutrality, wide availability all over the world and low cost, makes it a key player in the sustainable energy sector. Low bulk density is one of the challenges facing its utilization, which can be tackled through densification technology. The research is aimed at producing solid biofuel using three different agricultural by-products (corn cobs, rice husk and peanut shells) and testing their mechanical durability and thermochemical properties. Thermogravimetric analysis and differential scanning calorimetry (TGA-DSC) were used in measuring the thermal decomposition behavior of the biomass, and briquettes were produced through densifying the 8 mm fraction of the samples at a pressure of 18 MPa. Associated emissions were measured during the combustion of briquettes. Rice husks and corn cobs have similar thermal decomposition patterns at a temperature range of 300 – 500 °C, with rice husks having a higher amount of inorganic components. Peanut shells present a steady weight loss at a wide temperature range of 300 – 900 ºC. Briquettes produced from peanut shells have the highest mechanical durability of 95.37%, while that of corn cobs completely crumbled during the test. Rice husk briquettes have the lowest CO emission of 493.05 $mg.m^{-3}$. Corn cobs briquettes present the highest CO and NO_x emissions, which can be minimized by monitoring and controlling the excess air ratio, thereby increasing the efficiency of the combustion process.

Keywords: combustion, briquetting, emissions, thermal decomposition, TGA, DSC

7.1. Introduction

The global energy demand is getting higher due to industrial development and the rapid growth in population. Oil and gas, which are considered non-renewable and polluting fuels, are the dominant energy source used in the industries despite their proven impact on the climate (Ersoy & Ugurlu, 2024; Ladanai & Vinterbäck, 2009). Continued dependence on those non-renewable energy sources will put global energy at risk because of their limited reserves. Transition to other renewable sources becomes necessary to ensure energy security and meet the global energy demand (Benti et al., 2021). This transition will not only secure energy but will also ensure a clean and healthy environment, free from harmful emissions. Solar, wind, hydro and biomass are among those renewable sources of energy that can be adopted as alternatives to polluting ones.

Biomass is an organic material derived from plants and animal matter such as wood, forest waste, agricultural residues, manure and algae (Banerjee, 2023; Benti et al., 2021; Chen et al., 2015; Wang et al., 2021). It is the most common and widely available among all forms of renewable energy sources (Ladanai & Vinterbäck, 2009; Niyogi et al., 2024). Its capability of providing all forms of energy (solid, liquid and gas) through different conversion processes, such as biochemical, thermochemical and physicochemical, makes it versatile for adaptation in the renewable energy sector (Banerjee, 2023; Chen et al., 2015; Ersoy & Ugurlu, 2024; Ladanai & Vinterbäck, 2009; Niyogi et al., 2024). The composition and characterization of the biomass determine the form of energy that it will be suitable for production (Banerjee, 2023; Niyogi et al., 2024). Low cost, carbon neutrality and wide availability in different forms are among the factors encouraging the utilization of biomass as feedstock for biofuel production, which is an alternative fuel that can be used in place of polluting fuels (Niu et al., 2016).

The agricultural sector is a sector that generates a lot of by-products, which are mostly considered by the farmers and processors as waste, especially in the developing world. Proper utilization and management of these by-products can sustainably contribute to economic value generation and waste management (Niyogi et al., 2024). These developing countries are believed to have large arable land that is used for agriculture and contributes to their economic development (Benti et al., 2021; Jekayinfa et al., 2020). These by-products, including straws and husks, are promising options for densified fuel production due to their low cost and ease of access (Chico-Santamarta et al., 2012). Biomass can be obtained across all regions around the world, depending on the type of crops that are produced in the region (OPEC, 2024). It can also be produced massively, despite its ability to be obtained from different sources (Niu et al., 2016). As the third most widely used energy source after oil and coal (Tumuluru et al., 2011), possessing good energy potential, biomass is ineffectively used in rural areas for cooking and heating (Benti et al., 2021; Thengane et al., 2022).

Transportation, storage and handling are among the main challenges of biomass utilization as a source of energy, posed by its low bulk density (Ibitoye et al., 2021; Tumuluru et al., 2011). A large amount of space is required for storing a small quantity of herbaceous biomass and grasses by weight. Likewise, transportation, more energy and time will be needed to move it from one place to another (Chico-Santamarta et al., 2012; Tumuluru et al., 2011). Other challenges of biomass utilization as a source of energy are the high ash moisture contents, which cause problems to the combustion facility and incomplete combustion, leading to the emission of unwanted gases (Niu et al., 2016). Unlike woody biomass, whose bulk density is around 150-200 $kg.m^{-3}$, the bulk density of other agricultural by-products such as grasses and straws is within the range of 80-100 $kg.m^{-3}$ (Tumuluru et al., 2011). Apart from transport challenges, this low bulk density increases the chances of emitting associated GHG during direct combustion (Chico-Santamarta et al., 2012), which is the common practice in the rural areas of developing countries (Bappah et al., 2024).

The increasing global biomass and biofuel production arises from the surging price of fossil fuels, an increase in environmental concern over their impacts and a risk on their reserves, which is forecasted to be a challenge to the security of energy in the years to come. The global bioenergy potential is expected to meet the global energy demand by the year 2050 (Errera et al., 2023; Ladanai & Vinterbäck, 2009), which will be nine times the current primary production (Errera et al., 2023).

Pelletization and briquetting are the major densification technologies that are used in biomass to unify the physical properties, without affecting the chemical composition (Kumar et al., 2012; Ray et al., 2013). This technology is less expensive (IEA, 2019) and reduces the bulkiness of the biomass, thereby making transportation costs lower, making storage space less, improving the shelf life and making handling and manipulation easier (Thengane et al., 2022; Williams et al., 2016). It involves compressing the biomass at high pressure to form solid materials of uniform shapes whose bulk density is far greater than the original biomass (Ibitoye et al., 2021; Mohammed et al., 2023).

The quality of a densified biomass is determined from the strength used for the densification and the durability of the densified fuel, all of which can be affected by the pressure used for densifying the biomass, the diameter of the die as in the case of pellet, the binder used, where required and the compression or pre-heating temperature (Tumuluru et al., 2011).

The thermal degradation of biomass or solid biofuel can be presented as the thermal decomposition of different components of the biomass at different phases (P. T. Williams & Besler, 1993). Some components decompose at higher temperatures, while some at lower or moderate temperatures. The decomposition will therefore be attributed to the composition of the original biomass (Shafizadeh & McGinnis, 1971). The decomposition of the hemicellulose part of the biomass starts at 200 ºC, and cellulose and lignin slightly decompose within the temperature range of 250 – 300 ºC (Thengane et al., 2022). Degradation of hemicellulose is at the temperature range of

200 – 450 ºC, that of cellulose is 275 – 500 ºC, whereas lignin degrades at 130 – 900 ºC (Granados et al., 2017).

7.2. Methodology

7.2.1. TGA-DSC Analysis

Thermal behaviors of the biomass, including decomposition, phase transition and thermal stability, were measured using a thermogravimetric analyzer, Setaram Setsys Evolution (model S60, Setaram Instrumentation, Tours, France). Dried analytical sample was used for thermogravimetric analysis, where the loss in mass of the biomass was studied as a function of temperature and heat flow. Thermal decomposition of the biomass was carried out at a heating rate of 10 ºC.min^{-1} (S. Wang et al., 2021) under an air atmosphere.

7.2.2. Biofuel Production

BrikStar hydraulic briquetting press (model CS 25, Briklis, Malšice, Czech Republic), with a compression pressure and cylinder diameter of 18 MPa and 65 mm, respectively, was used to produce the briquettes. The biomass was first crushed through a sieve size of 8 mm as recommended by Samson et al. (2005), using a hammer mill.

7.2.3. Mechanical durability

The mechanical durability of briquettes was measured using a briquette mechanical durability drum (BT 105, Czech Republic), according to the standard ISO 17831-2 (2015). 2 ± 0.1 kg of the briquettes were first sieved through a 31.5 mm screen to remove fine particles before subjecting them to collisions inside the rotation drum at 21 ± 0.1 rpm for 5 min, after which they were sieved again through a 31.5 mm screen and weighed. The durability was calculated using equation 1.

$$DU = \frac{m_2}{m_1} \times 100 \quad (7.1)$$

Where DU is the mechanical durability (%), m_1 is the mass of the briquette before the test (g) and m_2 is the mass of the briquette after testing and sieving (g).

7.2.4. Combustion test

The selected biomass samples are tested for emission concentrations of carbon monoxide and nitrogen oxides during combustion tests on a grate-fired combustion unit. The combustion tests are carried out under controlled operating conditions, such as flue gas temperature and excess air ratio. For the combustion tests, a combustion unit with a fixed grate and manual fuel feeding is used. Similar units are commonly used for residential heating. This combustion unit was also selected for its ability to regulate the supply of combustion air. A primary-to-secondary ratio of 3:1 was maintained. The total amount of air for each combustion test corresponded to the values determined by the stoichiometry of the individual biofuel samples.

The nominal thermal output of the combustion unit is 8 kW, with the standard fuel consumption of plant-based material specified by the manufacturer at a value of 2,5 $kg.h^{-1}$. During the combustion tests of the biomass samples, the mass flow rates into the combustion unit are maintained to ensure the nominal thermal output at 80% efficiency. Based on the elemental composition and calorific value of the individual samples, the mass flow rate of the samples for the combustion test is determined. The actual mass flow rate during the conducted tests, for a combustion unit with an output of 8 kW and an average thermal efficiency of 80%, is calculated using stoichiometric calculations based on the elemental analyses of the biofuel samples and the required excess air ratio $n = 2.1$.

The mass flow rate of biofuel for determining the thermal input of the solid biofuel combustion unit is established as follows: the required mass flow rate of fuel to be maintained during the test is preliminarily calculated based on previous stoichiometric calculations, into which the required values are inserted P_k and q_n:

inserted P_k and q_n:

$$\dot{m}_{pv} = \frac{P_k \cdot 100}{q_n \cdot \eta} \tag{7.2}$$

where:

$\dot{m}_{pv}$ is the mass flow rate of fuel supplied to the combustion chamber ($kg.s^{-1}$),

P_k is the nominal thermal output of the boiler (W),

q_n is the net calorific value of fuel ($J.kg^{-1}$),

η is the efficiency of the combustion unit (%).

During the combustion process, the supply of primary combustion air was controlled. The amount of combustion air was monitored by measuring the oxygen concentration in the flue gas using the flue gas analyzer.

Emission concentrations were measured using a flue gas analyzer Madur GA-60 (madur Polska Sp. z o.o., Zgierz, Poland) (Figure 7.1). During the measurement, the analyzer monitored the ambient temperature, flue gas temperature and concentration of O_2, CO, NO, and NO_2 in flue gas. Technical data of the analyzer is provided in Appendix A. Before measuring each sample, the analyzer was calibrated. The sensor signals are proportional to the volumetric concentration of the measured components in ppm. The concentrations of dry flue gas components were converted to standard conditions (temperature 0 °C and pressure p = 101,325 kPa) and concentrations in $mg.m^{-3}$ at the reference oxygen content of 10 % in the flue gas. The emission measurement results were processed using regression analysis to express the dependence of carbon dioxide and nitrogen oxides on the air excess coefficient and flue gas temperature.

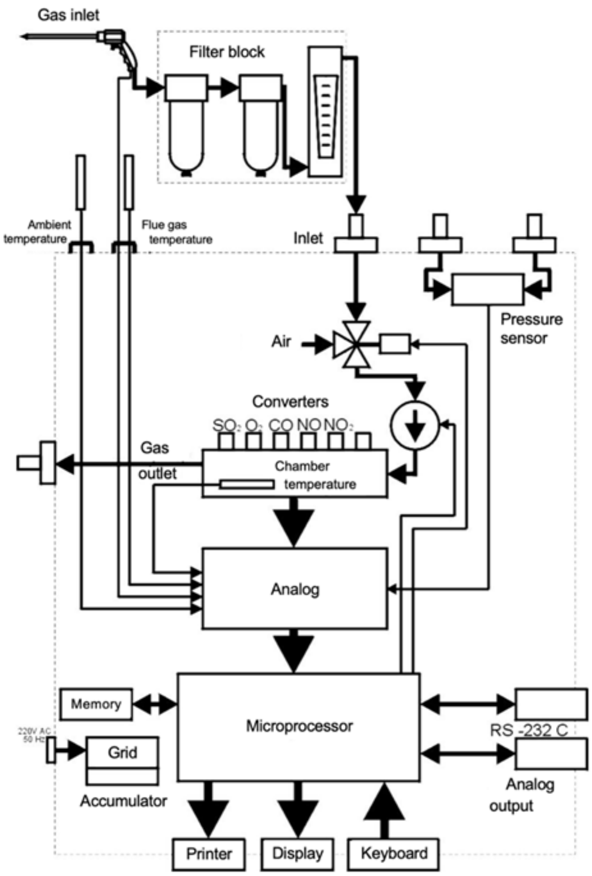

Figure 7.1. Block diagram of the device GA-60 (adjusted)

All measured values of emission concentrations are given in ppm and %. Concentrations in ppm are converted to mass concentrations in $mg.m^{-3}$. For converting fractional composition in ppm (1 ppm = 1 cm^3 of pollutant in 1 m^3 of air) to mass concentration in $mg.m^{-3}$ (mass of $1cm^3$ of pollutant in mg in $1m^3$ of air), equation 7.3 applies:

$$1ppm = \frac{M}{m} = \frac{M}{22,414} = 0,0446M \quad (mg.m^{-3}) \qquad (7.3)$$

where: M – molecular weight of the pollutant ($mg.mol^{-1}$);

m – molar volume of the pollutant (22,414 $cm^3.mol^{-1}$).

The values used for the conversion are presented in Appendix B

7.3. Results and discussion

7.3.1. TGA-DSC Analysis

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were used to determine the change in weight of the biomass resulting from heat flow during thermal decomposition. The reactions are generally endothermic with varying peak heat flow. The decomposition process of biomass is determined by weight loss, which can be divided into various stages. Initial weight gain was observed for all biomass, at the temperature of 40 ºC, during which an exothermic reaction occurs, which may result from the relative humidity (Dongargaonkar et al., 2020; Fan, 2008). For corn cobs, initial weight was regained at 220 ºC after weight gain, while rice husks and peanut shells returned to their original weight at 260 ºC and 115 ºC, respectively. This results from losing the moisture gained on trying to reach an equilibrium condition (Wang et al., 2021). In the case of corn cobs, a weight loss of 5% was observed at 265 ºC, with an exothermic reaction, reaching a peak at 280 ºC (Figure 7.2), indicating the emission of remaining moisture and some volatiles (Wang et al., 2021). Another weight loss of about 57% occurs at the temperature range of 300 ºC to 400 ºC, when an endothermic reaction reaches its peak at 320 ºC, followed by a small exothermic reaction, resulting from the decomposition of some impurities or cellulose materials, which were reported by Chen et al. to decompose at 315 – 400 ºC (D. Chen et al., 2015). Thermal degradation of the major organic compounds, such as polymers or hydrocarbons, which depend on the molecular structure, occurs at 200 – 500 ºC. This reaction indicates the decomposition of small organic compounds and glucose (Wang et al., 2021; P. T. Williams & Besler, 1993). A total weight loss of 90%, which indicates complete decomposition of all organic impurities, occurs during the peak endothermic reaction at 460 ºC. Less than 10% of the carbonized substance or non-volatile components of the material were left after complete decomposition at 1000 ºC.

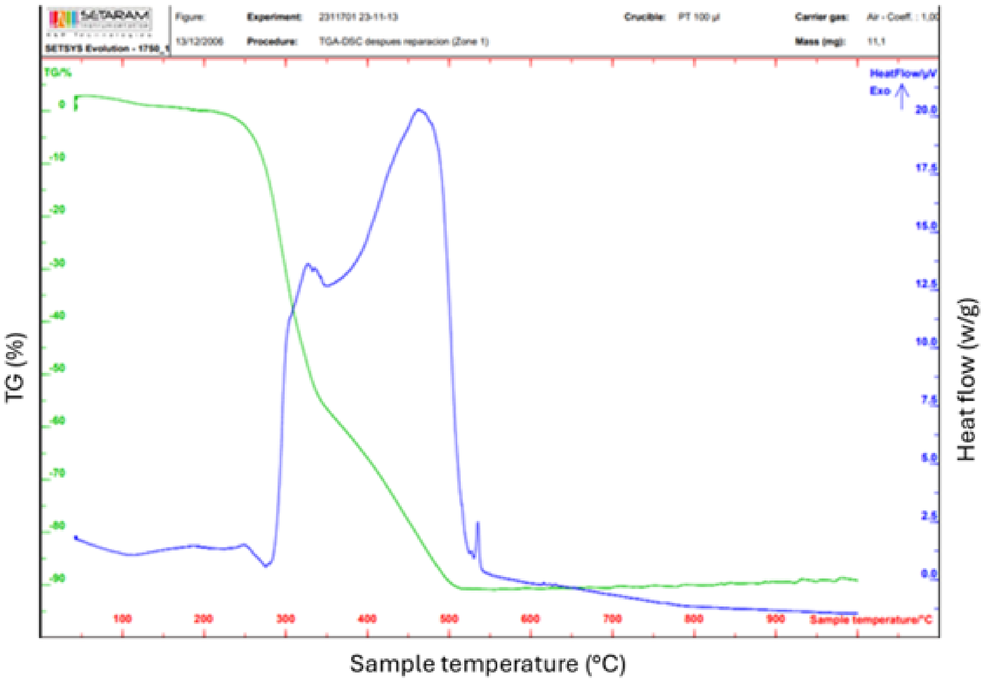

Figure 7.2. Thermal decomposition of corn cobs

In the case of rice husks, the TGA-DSC is similar to that of corn cobs with minor differences in the patterns of weight loss and heat flow (Figure 7.3). An endothermic reaction leading to a weight loss of 40% at the temperature range of 260 °C to 330 °C was observed from rice husk, resulting from decomposition of organic substances and lignin (D. Chen et al., 2015; Granados et al., 2017; Lu et al., 2012). The last weight loss occurs when the endothermic reaction reaches its peak at around 480 °C, indicating degradation of other organic compounds (Williams & Besler, 1993). The major decomposition with steep loss of weight occurs between 260 – 500 °C with heat absorption for breaking down the molecular bonds, after which it starts to stabilize. No weight loss was observed after 510 °C, indicating the final stage of the decomposition process, with over 20% of inorganic or non-volatile compounds. The high amount of inorganic compounds may result from the high ash content of the rice husk, which cannot be thermally decomposed.

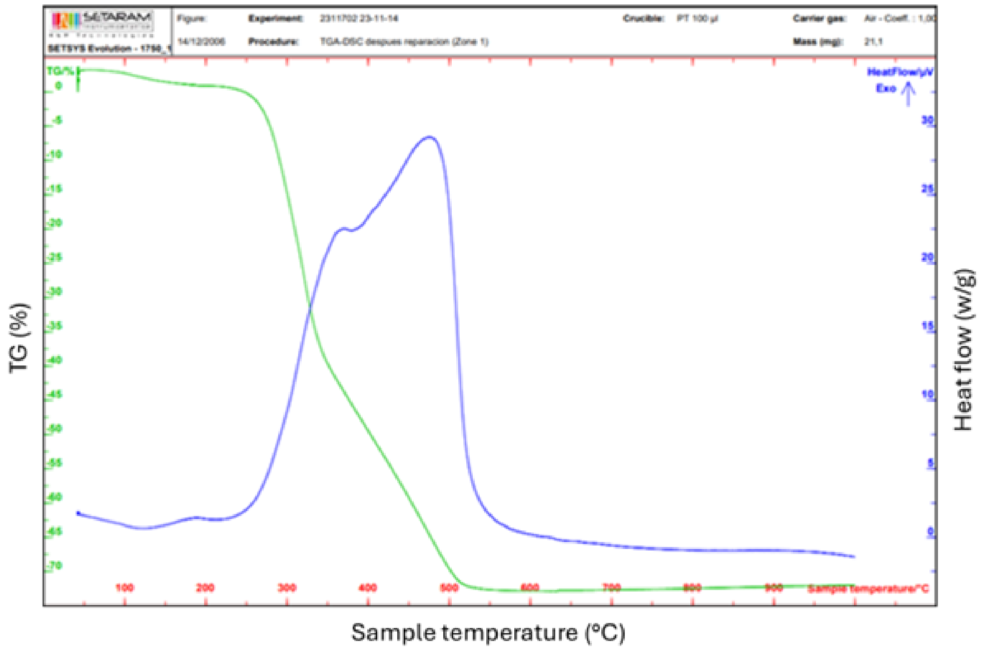

Figure 7.3. Thermal decomposition of rice husks

For peanut shells, a weight loss of 5% was observed with an endothermic reaction at 230 ºC. At 200 ºC to 330 ºC, a steep weight loss with high heat flow occurs, indicating an endothermic reaction (Figure 7.4). The peak endothermic reaction was reached at around 370 ºC with a weight loss of 70%. A total weight loss of 90% occurred at 840 ºC, indicating total decomposition of lignin (Granados et al., 2017). After which, no further weight loss was observed. The thermal decomposition of peanut shells is characterized by steady weight loss across a broader temperature range of 300 – 900 ºC, which can be associated with the sequential degradation process of the biomass and subsequent slow release of volatile compounds.

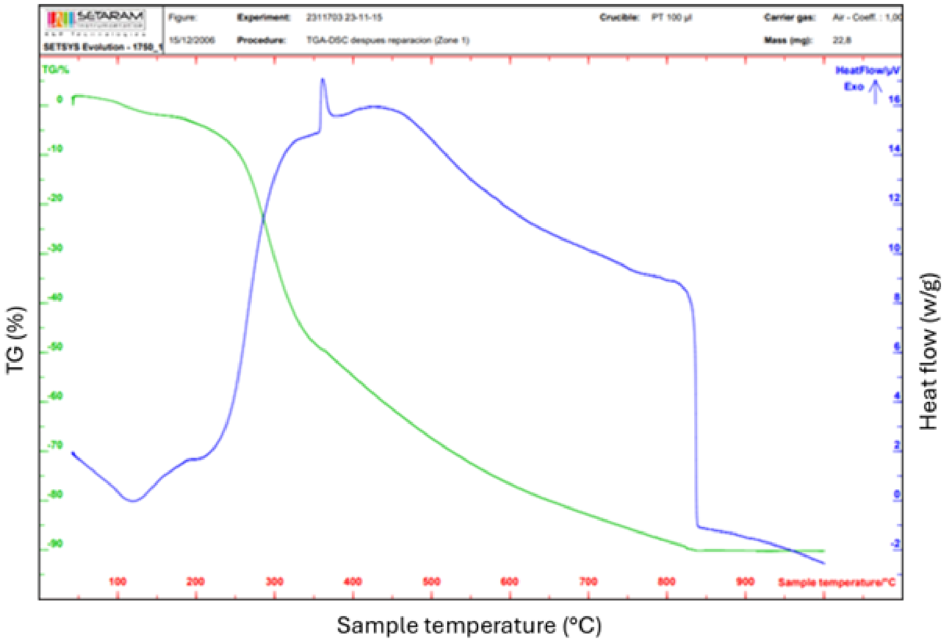

Figure 7.4. Thermal decomposition of peanut shells

7.3.2. Mechanical durability

The mechanical durability, which measures the resistance to abrasion and possible causes of wear and dust or fine particles formation during transportation (Chico-Santamarta et al., 2012) of the briquettes produced from peanut shells, rice husks and corn cobs was measured to be 95.37%, 82.38% and 0%, respectively. Out of these three briquettes, peanut shell briquettes are expected to resist handling and manipulation more than others, whereas corn cob briquettes will not resist any (Figure 7.5).

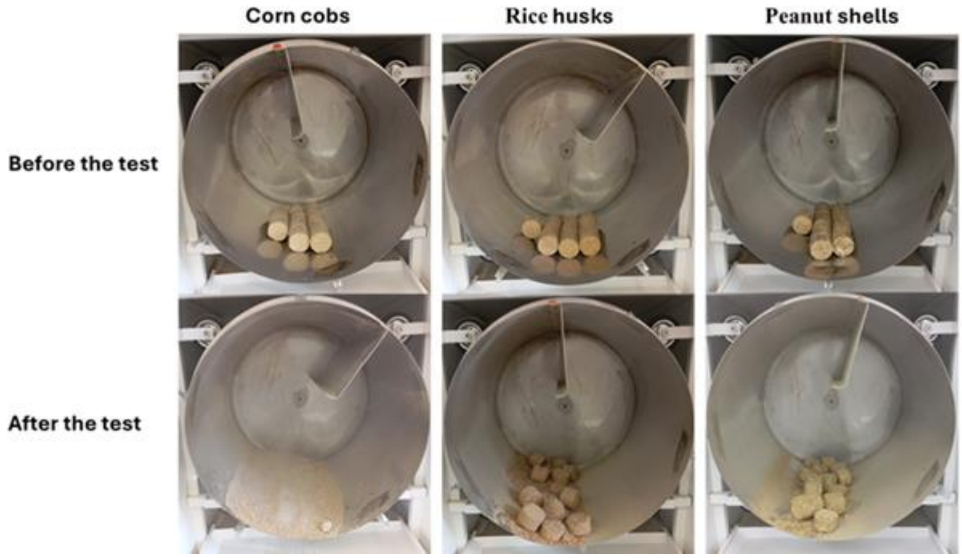

Figure 7.5. Mechanical durability test

While about 4.63% of peanut shell briquettes and 17.62% of rice husk briquettes may be lost as dust and small particles during handling and transportation, the whole corn cob briquettes will completely crumble. This is similar to what was reported by Gendek et al., on durability of briquette produced from larch, which happens to be 87.58%, therefore, about 12% can crumble during handling and transportation operations (Gendek et al., 2018). The crumbling of the corn cobs briquettes may result from the pith of the corn cobs, which is a spongy, soft material located at the center of the cob. A 0% durability was also reported from corn cobs briquettes by Kaliyan and Morey, and was discovered to significantly improve by preheating at 85 ºC (Kaliyan & Morey, 2010). A similar result on the durability of peanut shells was also reported by Elsisi et al. and was found to increase by decreasing particle size (Elsisi et al., 2025).

A binder and smaller particle sizes were reported to be used in most of the research where densified biofuel is produced from corn cobs (Akintaro et al., 2017; Aransiola et al., 2019; Birhanu Oliy & Tesfaye Muleta, 2020; C.V et al., 2022; Oyewusi et al., 2019), which improves the mechanical durability and makes handling and transportation possible. Torrefaction of the corn cobs before densification may improve the binding ability and mechanical durability (Akintaro et al., 2017; Oyewusi et al., 2019).

7.3.3. Combustion test

As shown by the results of the combustion tests, high average carbon monoxide (CO) emission concentrations were observed during the combustion of corn cob briquettes (Table 7.1). This means emission concentrations remain high even at the minimum measured CO emission level, while the requirement for operating this type of small combustion device with manual fuel feeding is on average below 2000 mg.m^{-3} at a reference O content of 10% in the flue gas under standard conditions. Such high emission concentrations were reported on the combustion of untreated grape pomace (Malaťák et al., 2022), rapeseed straw (Malaťák et al., 2024), and in other secondary agro-products (Souček & Jasinskas, 2020). The lowest average CO emission concentrations of 493.05 mg.m^{-3} were determined in rice husk briquettes. Biofuel samples from peanut shells reach average CO emission concentrations above 1,500 mg.m^{-3} at a reference oxygen content of 10% in the flue gas under normal conditions. For this sample, it is necessary to monitor the emission concentration profile of CO, as controlled combustion can reduce these emission concentrations to a minimum, thereby increasing the efficiency of the combustion process (Eskilsson et al., 2004). The value of flue gas temperature and excess air coefficient are decisive for the optimization of the combustion process (Eskilsson et al., 2004). According to the Nigerian National Environmental Standards and Regulations Enforcement Agency (NESREA), the maximum permissible CO limit is 400 ppm (NESREA, 2014), which is fulfilled by rice husk briquettes at an average level and by other biofuel samples at minimal levels.

Table 7.1. Mean emission concentration results from biomass samples

		T_{spalin}	O_2	n	CO	CO	CO (O_2=10 %)	NOx	NOx	NOx (O_2=10 %)
		°C	**%**	**-**	**ppm**	**mg.m^{-3}**	**mg.m^{-3}**	**ppm**	**mg.m^{-3}**	**mg.m^{-3}**
Peanut shells	Mean	365	13.16	2.73	1214	1518.59	1578.18	76	156.74	161.80
	s	22	1.12	0.38	579	724.38	1.84	13	27.22	3.96
	Max	411	15.25	3.65	2514	3143.62	1582.13	111	227.89	168.30
	Min	333	10.66	2.03	112	140.05	1575.09	48	98.55	153.67
Rice husks	Mean	319	12.82	2.58	394	493.05	449.29	77	158.44	155.86
	s	14	0.57	0.19	215	269.24	192.32	14	27.74	10.72
	Max	352	14.29	3.13	899	1124.15	1288.86	118	242.27	177.20
	Min	278	11.09	2.12	131	163.81	280.13	38	78.02	113.80
Corn cobs	Mean	312	12.80	2.62	2418	3024.02	2954.47	129	264.68	260.16
	s	71	1.16	0.42	1549	1937.23	847.72	40	82.26	53.60
	Max	422	15.43	3.77	7163	8956.95	6000.00	201	412.67	306.40
	Min	155	10.26	1.95	282	352.63	2104.00	25	51.33	72.29

The requirement for average nitrogen oxide emission concentrations, where the limit value is 250 mg.m^{-3} at a reference oxygen content of 10% in the flue gas under standard conditions, is fulfilled according to legal regulations ČR č. 201/2012 Sb. The Air Protection Act for samples from rice husks and peanut shells. Corn residues have the highest average emission concentrations of nitrogen oxides. These emissions are also consistent with the maximum permissible NOx emission of 244 ppm set by the NESREA (NESREA, 2014). The increased emission concentrations may be caused by a higher N content in the biofuel sample itself, as has also been observed in other fuels (Díaz-Ramírez et al., 2014). Another possible cause of higher nitrogen oxide emission concentrations in biofuel samples from corn residues is the measured high maximum flue gas temperature (422 °C), which promoted the formation of high-temperature NO_x emissions (Díaz-Ramírez et al., 2014).

Peanut shells

The results of carbon monoxide emission concentration profiles for biofuel samples from peanut shells indicate the influence of operational parameters of the combustion process, such as the excess air coefficient and combustion temperature, on the emission characteristics themselves (Juszczak, 2016). Optimization of the determined CO emission concentrations in small combustion devices is often difficult to achieve (Juszczak, 2016). Optimization can be carried out based on measured carbon monoxide concentration profiles with respect to operational parameters such as the excess air coefficient and flue gas temperatures (Klauser et al., 2018; Malaťák et al., 2022). Another way to prevent high CO concentrations is the selection of appropriate fuel and combustion equipment (Maj et al., 2024; Malaťák et al., 2020). The results of the carbon monoxide emission concentration profiles show an initial decrease followed by an increase in concentration with a continuously increasing excess air coefficient (Figure 7.6). Optimization of CO emission concentrations is only possible if the combustion process is optimized to an excess air coefficient value in the range of approximately 2.8 to 3.0. When the excess air coefficient is exceeded, the combustion chamber cools down, leading to an increase in CO emission concentrations.

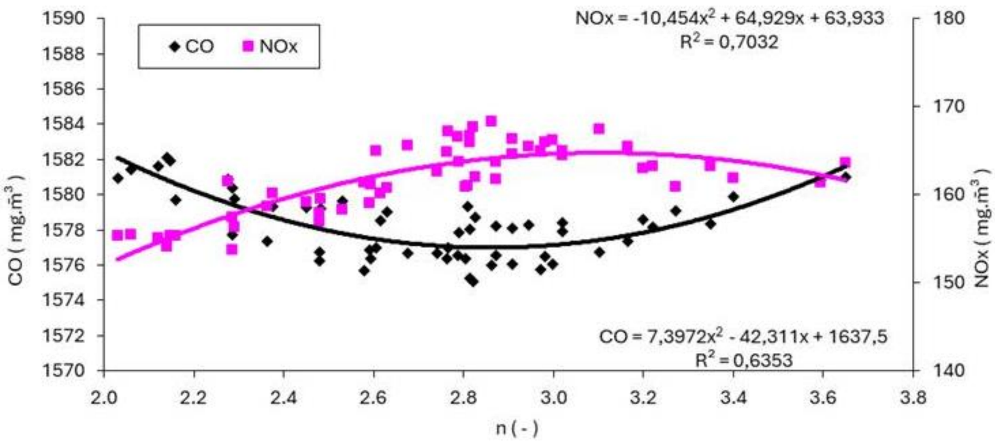

Figure 7.6. Trend of emission concentrations CO and NOx depending on the excess air coefficient

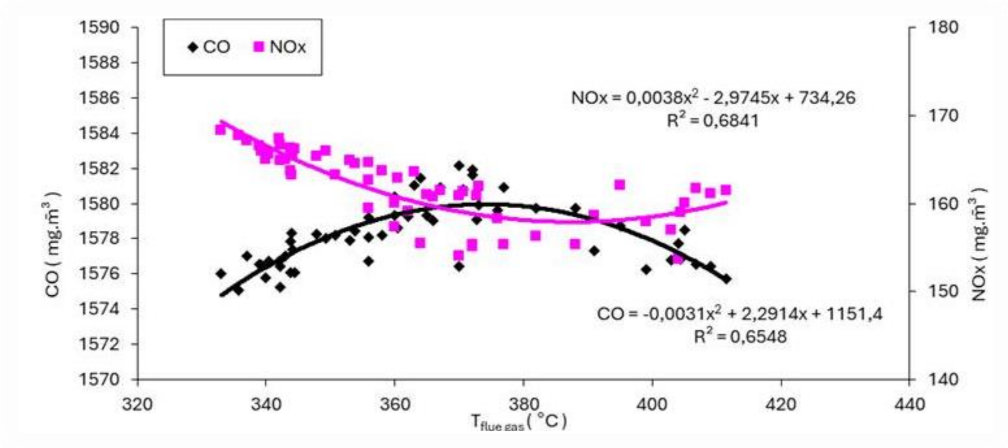

Figure 7.7. Trend of emission concentrations CO and NOx depending on flue gas temperature

In this measurement, the expected trend of carbon monoxide emission concentrations depending on temperature, as established in other similar studies (Maj et al., 2024; Malaťák et al., 2020), was not observed. With increasing temperature (Figure 7.7), the gas-phase combustible part of the fuel in the form of carbon monoxide did not burn off better, instead, its concentration first increased and then, after exceeding a flue gas temperature of approximately 378 °C, gradually decreased. One possible explanation for this phenomenon is a lack of combustion air or significant cooling of the flue gases, and consequently, cooling of the combustion chamber.

With the increasing excess air coefficient, the flue gas temperature decreases, as can be seen from the trend (Figure 7.8), and this leads to increasing concentrations of CO (Eskilsson et al., 2004). Unfortunately, in this measurement, the reliability parameter is at a very low value.

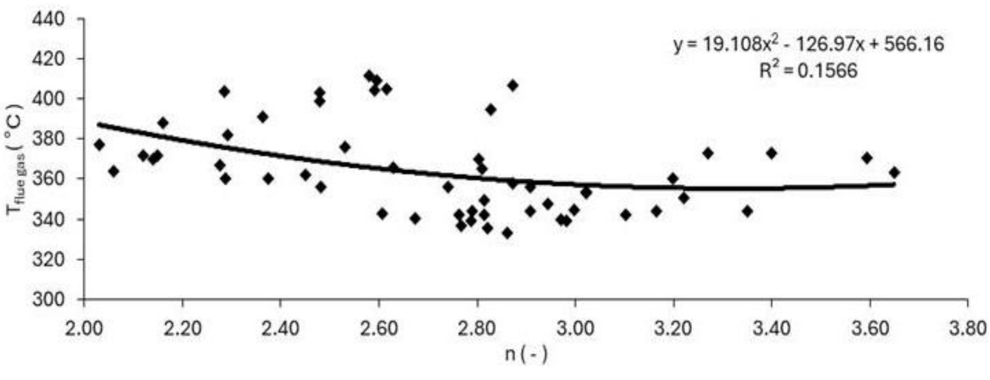

Figure 7.8. Dependence of flue gas temperature on excess air coefficient

Emission concentrations of NO_x increase with the rising excess air coefficient (Figure 7.6), which is also confirmed from other similar biofuel samples (Díaz-Ramírez et al., 2014). A high amount of combustion air cools the flue gases (Figure 7.8). With increasing flue gas temperature, the emission concentrations of NO_x decreased (Figure 7.7). This indicates that despite the achieved high flue gas temperatures, a smaller amount of combustion air was involved in the actual combustion, which resulted in a decrease in the emission concentrations of nitrogen oxides in the flue gases. Similar dependency trends are primarily observed during combustion of herbaceous biomass (Houshfar et al., 2012; Malaťák et al., 2024) and also from wastes of the agri-food sector, e.g. residues from grape processing (Maj et al., 2024; Malaťák et al., 2022). After the flue gas temperature exceeds 390 °C, there is a gradual increase in nitrogen oxide emission concentrations (Figure 7.7), mainly due to the high amount of combustion air and the flue gas temperature. If the combustion processes continue at high temperatures and excess air coefficient, optimal conditions for the formation of high-temperature nitrogen oxide emissions would arise (Díaz-Ramírez et al., 2014).

Rice husks

The resulting values from the measurement of carbon monoxide emission concentration profiles for rice husk briquettes indicate a significant influence of operational parameters of the combustion process, such as the excess air coefficient and combustion temperature (Juszczak, 2016). Optimization of combustion processes can be achieved based on measured carbon monoxide concentration profiles with respect to operational parameters such as the excess air coefficient and flue gas temperature (Klauser et al., 2018; Malaťák et al., 2022), or by selecting an appropriate fuel (Maj et al., 2024; Malaťák et al., 2020), at which average emission concentrations can be optimized to meet the required level, thereby simultaneously increasing the efficiency of the combustion device (Eskilsson et al., 2004). The results of the carbon monoxide emission concentration profile indicate a rapid increase in concentrations with increasing excess air coefficient (Figure 7.9). Emission concentrations of the CO increased from 280 to 1288 $mg.m^{-3}$. Such high concentrations were determined during the combustion of herbaceous biomass (Malaťák et al., 2017) and were exceeded several times during the combustion of other organic wastes (Souček & Jasinskas, 2020). Optimization of the excess air coefficient is required in these cases because regulating the excess air coefficient can reduce emissions to the desired levels, as demonstrated in the study of Johansson et al. (2004) during the combustion of pellets, as well as Malaťák et al. (2022) during the combustion of briquettes.

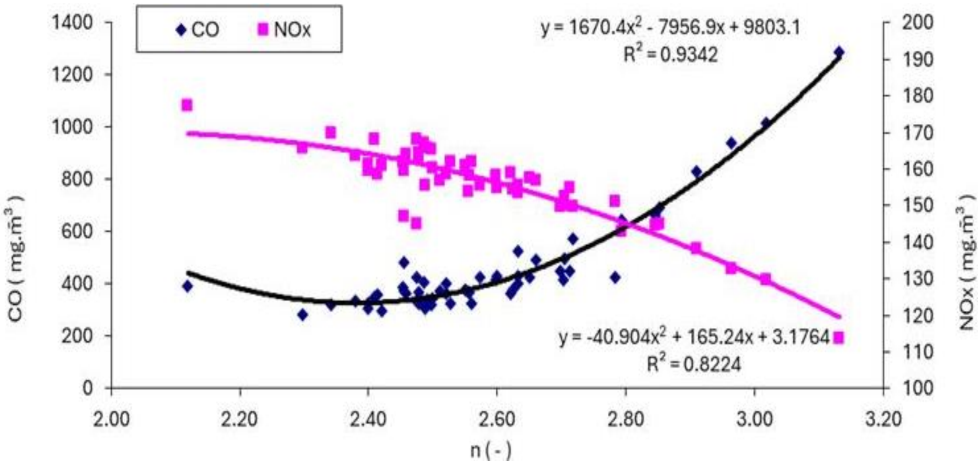

Figure 7.9. Trend of emission concentrations CO and NOx depending on the excess air coefficient

On one hand, emission concentrations of CO increase with the increasing excess air coefficient, on the other hand, they decrease with increasing flue gas temperature (Figure 7.10). The determined profiles are consistent with results from biomass combustion (Juszczak, 2016; Malaták et al., 2020; Malaťák et al., 2024). With an increasing excess air coefficient, the flue gas temperature decreases, as shown in Figure 7.10, which leads to a reduction in carbon monoxide concentrations with increasing flue gas temperature. Similar trends have also been observed for comparable fuels (Eskilsson et al., 2004; Malaťák et al., 2022).

NO_x emission concentrations decrease with increasing excess air coefficient (Figure 7.8), which is also confirmed for the other similar biofuel samples (Malaťák et al., 2024). A high amount of combustion air cools the flue gas (Figure 7.10). With increasing flue gas temperature, NO_x concentrations increase (Figure 7.10), as with other biofuels (Díaz-Ramírez et al., 2014). During the measurements, a gradual increase in NO_x emission concentrations was observed with increasing flue gas temperature. If the combustion processes were to continue at high temperatures, optimal conditions for the formation of high-temperature NO_x emission concentrations would be created (Díaz-Ramírez et al., 2014).

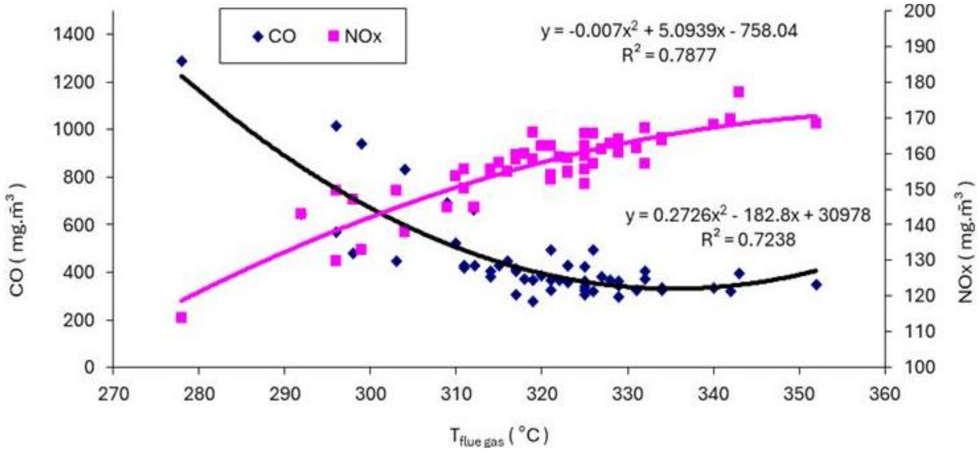

Figure 7.10. Trend of emission concentrations CO and NOx depending on the flue gas temperature

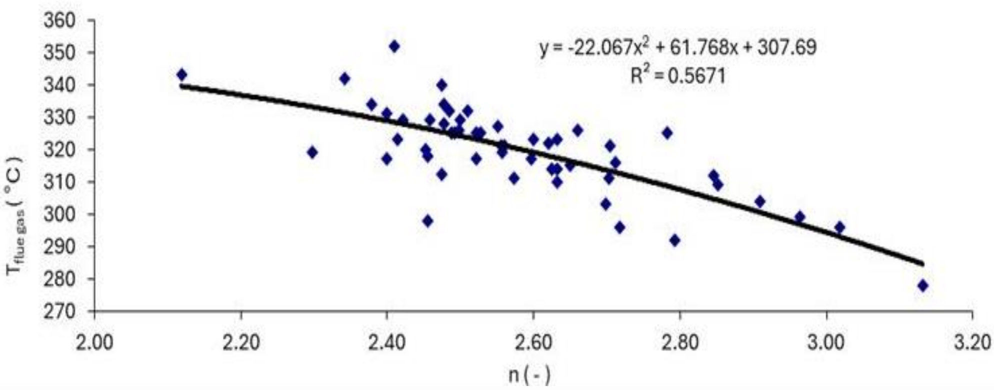

Figure 7.11. Dependence of flue gas temperature on the excess air coefficient

Corn cobs

The determined CO emissions profiles for biofuel samples from corn cobs indicate a significant influence of operational parameters of the combustion process, such as the excess air coefficient and combustion temperature levels (Juszczak, 2016). The excess air coefficient had a significant impact on the CO emission concentrations, which exceeded the permissible limits from 2000 to 6000 mg.m^{-3}. The reduction of CO emission concentrations is necessary in this case to meet the required efficiency of the combustion device (Eskilsson et al., 2004).

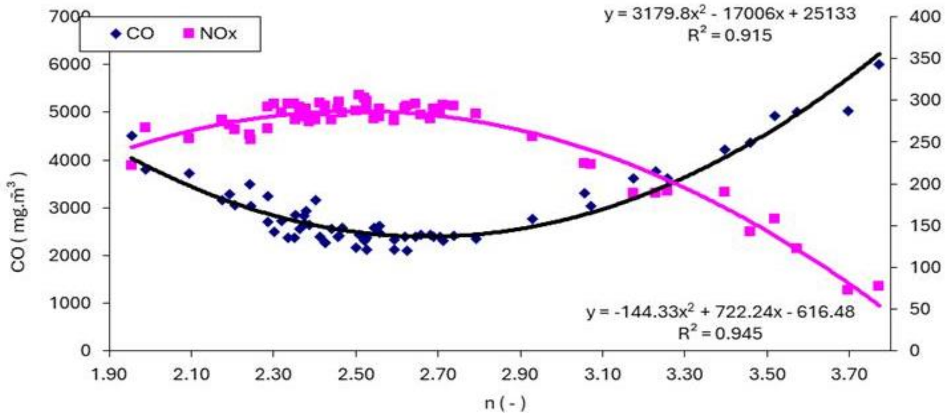

Figure 7.12. Trend of emission concentrations CO and NOx depending on excess air coefficient

The results of the CO emission concentration profile as a function of the excess air coefficient indicate decreasing concentrations up to an excess air coefficient value of 2.7, after which the CO concentrations increase continuously with further increases in the excess air coefficient (Figure 7.12). Optimization of CO emission concentrations is only possible if the combustion process is optimized to an excess air coefficient value of 2.7. Exceeding this value leads to cooling of the combustion chamber, resulting in an increase in CO emission concentrations. High concentrations have also been determined during the combustion of herbaceous biomass (Malaťák et al., 2017) and was reported to exceed it several times during the combustion of the organic wastes (Souček & Jasinskas, 2020). Optimisation of the excess air coefficient is required to reduce emissions to low levels, as demonstrated in the study by Johansson et al. (2004) when burning pellets, and when burning briquettes (Malaťák et al., 2022).

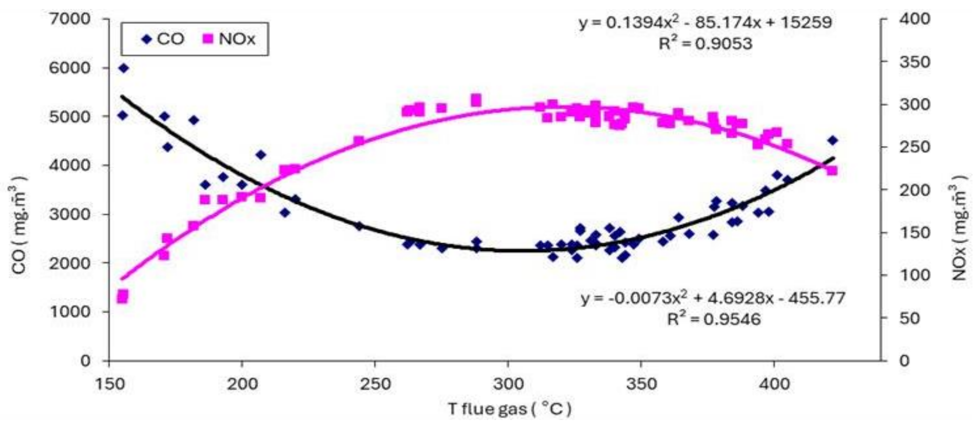

Figure 7.13. Trend of emission concentrations CO and NOx depending on flue gas temperature

As CO emission concentrations increase with the increasing excess air coefficient, they similarly decrease with increasing flue gas temperature at the initial stage, after which they increase on exceeding 310 °C (Figure 7.13). With an increasing excess air coefficient, the flue gas temperature decreases (Figure 7.14), leading to a decrease in CO concentrations with increasing flue gas temperature. Similar trends were reported on the combustion of relevant biofuel samples (Eskilsson et al., 2004; Malaťák et al., 2022).

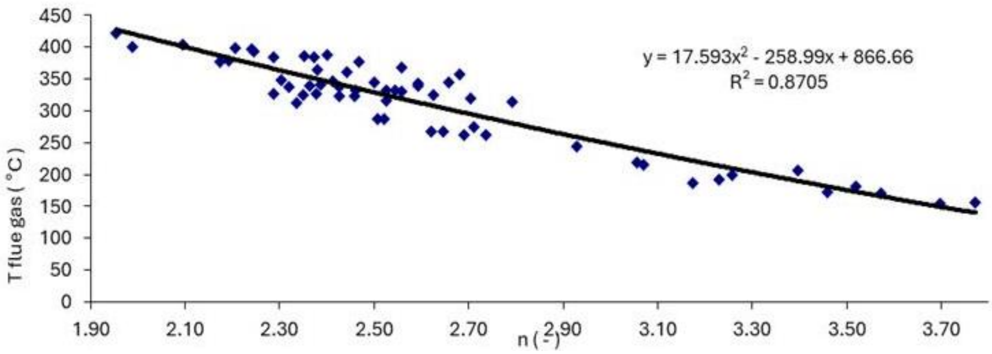

Figure 7.14. Dependence of flue gas temperature on the excess air coefficient

The resulting values of nitrogen oxides emission concentrations decrease with an increasing excess air coefficient (Figure 7.12), which has also been confirmed for other similar biofuel samples (Malaťák et al., 2024). Compared to other biofuel samples, corn residues exhibit a wide range of values, with measured concentrations from 72 to 306 $mg.m^{-3}$. A high amount of combustion air cools the flue gases (Figure 7.14). As the flue gas temperature increases, the emission concentrations of nitrogen oxides also increase (Figure 7.13), similar to other biofuels (Díaz-Ramírez et al., 2014). If the combustion process were to continue at elevated temperatures, conditions would be favorable for the formation of large concentrations of thermal nitrogen oxides (Díaz-Ramírez et al., 2014).

7.4. Conclusion

Weight loss with respect to heat flow during thermal decomposition of briquettes produced from peanut shells, corn cobs and rice husks reveals the phases at which different components of each by-product decompose. Rice husk and corn cobs with similar decomposition patterns attained 80% and 90% weight loss, respectively, at around 500 °C, indicating total decomposition of organic compounds, whereas peanut shells present a wide and steady weight loss with continuous heat flow up to 900 °C. Briquettes produced from peanut shells exhibit the highest mechanical durability of 95.38%, indicating their resistance to abrasion during handling, transportation and manipulation. This resistance reduces as the mechanical durability of the briquettes is reduced. While rice husk briquettes have a mechanical durability of 82.38%, corn cob briquettes didn't show any sign of durability, which indicates that they may completely crumble in the process of handling and manipulation. Crumbling of the corn cobs briquettes may result from the pith, which is a soft, spongy-like material at the center of the cobs with very low lignin content. Improvement of durability can be achieved by pre-treating the biomass, using a binder or using smaller particle sizes. Rice husk and peanut shell briquettes were discovered to emit lowest NOx concentration during combustion, which is far less than the maximum permissible emission set by the Nigerian National Environmental Standards and Regulations Enforcement Agency (NESREA). Unlike corn cobs with high NOx and CO content, which can be influenced by the excess air coefficient, rice husk briquettes appear to have the lowest CO emission concentration, slightly less than the NESREA's maximum permissible level. The high emission concentrations may result from the higher content of the concerned elements in the biofuel feedstock itself.

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7.6. Appendix

Appendix A. Analyzer technical data GA-60

Measured parameter/Measurement principle	**Range**	**Resolution**	**Sensor accuracy**
Ambient temperature/sensor Pt 500	0 – 100 ºC	1 ºC	± 2%
Flue gas temperature	0 – 1 300 ºC	1 ºC	± 5%
Sensor NiCr/ni (or PtRh/Pt)	0 – 1 600 ºC	1 ºC	± 2%
Electrochemical converter /oxygen (O_2)	0 – 20,95%	0,01%	± 2%
Electrochemical converter /carbon monoxide (CO)	0 – 20,000 ppm	1 ppm	± 5%
Electrochemical converter /nitrous oxide (NO)	0 – 5,000 ppm	1 ppm	± 5%
Electrochemical converter /nitrogen dioxide (NO_2)	0 – 800ppm	1 ppm	± 5%
Electrochemical converter/sulphur dioxide (SO_2)	0 – 2,000 ppm	1 ppm	± 5%
Pressure	± 50 hPa	0,01 hPa	
Bacharach soot number	0 - 9	1	
Nitrogen oxides (NO_x) as NO_2/calculation from NO+NO_2	0 – 6,000 ppm	1 ppm	
Excess air/calculation according to DIN/öNORM	1 - ∞	0,01	

Appendix B. Emission units' conversion

In practice, for conversions we use the values of *actual molar volumes of gases*, namely:

$$1 ppm SO_2 = \frac{64,05}{21,84} = 2,93 \text{ (mg.m}^{-3}\text{)}$$

$$1 ppm NO_2 = \frac{46,01}{22,41} = 2,05 \text{ (mg.m}^{-3}\text{)}$$

$$1 ppm CO = \frac{28,01}{22,40} = 1,25 \text{ (mg.m}^{-3}\text{)}$$

$$1 ppm NO = \frac{30,01}{22,41} = 1,34 \text{ (mg.m}^{-3}\text{)}$$

To convert the measured amounts of pollutants in wet flue gas (air) at temperature t and pressure p to standard conditions (0 °C; 101,325 kPa) and to adjust for the reference oxygen content in the flue gas, we use the following equations:

Calculation of the emission factor for standard conditions of wet flue gas:

$$E_v = \frac{273,15+t}{273,15} \cdot \frac{101325}{101325+p} \cdot E_n$$

Calculation of the emission factor for standard conditions of dry flue gas:

$$E_s = \frac{273,15+t}{273,15} \cdot \frac{101325}{101325+p} \cdot \frac{100}{100-w} \cdot E_n$$

Calculation of the emission factor for standard conditions of dry flue gas and reference oxygen content in the flue gas:

$$E_{sr} = \frac{273,15+t}{273,15} \cdot \frac{101325}{101325+p} \cdot \frac{100}{100-w} \cdot \frac{21-O_r}{21-O_p} \cdot E_n$$

Where in the equations:

E_n is the measured concentration of pollutants in 1 m^3 of flue gas under operating conditions ($mg.m^{-3}$),

E_v – concentration of pollutants in 1 m^3 of wet flue gas at standard conditions ($mg.m^{-3}$),

E_s – concentration of pollutants in 1 m^3 of dry flue gas at standard conditions ($mg.m^{-3}$),

E_{sr} – concentration of pollutants in 1 m^3 of dry flue gas at standard conditions and for the reference oxygen content in the flue gas ($mg.m^{-3}$),

t – operating flue gas temperature (°C),

p – pressure difference between operating pressure and normal pressure (Pa),

w – water vapor content in the flue gas (% vol.),

O_p – Oxygen content in the flue gas corresponding to operating conditions (measured) (% vol.),

O_r – reference oxygen content in the flue gas (% vol.).

CHAPTER 8 Conclusion

This study demonstrates that firewood and charcoal are the dominant cooking fuels used by over 60% of the households in northeastern Nigeria, despite their awareness of their impact on their health and the environment and the government's efforts to reduce deforestation. Even though 58% of the households are not fully satisfied with the cooking energy source, they have no option but to continue using it due to the high cost and difficulty in accessing non-polluting fuels. These results, therefore, suggest providing alternative energy sources for the households and making them available at a subsidized price, since majority of them are willing to accept but prevented by the cost and availability. This will reduce deforestation, ensure a healthy environment and help in achieving goals 7 and 3 of SDGs.

Rice, corn, millet, sorghum and peanut are among the major crops produced in Nigeria, from which rice husks, corn cobs, millet husks, sorghum husks and peanut shells are respectively generated as by-products. Peanut shells and corn cobs were discovered to be viable for solid biofuel production due to their high calorific values of 17.48 and 16.25 MJ.kg-1 and low ash content of 3.46 and 1.79%, respectively, which are in conformity with the relevant ISO standards (17225-6:2021 and 17225-7:2021). These by-products were therefore recommended for detailed study to confirm their viability for combustion fuel. Due to their potential as supplements for animal feed, sorghum husks and millet husks should not be considered for energy to avoid competition.

Despite its high ash content and low calorific value, rice husks are highly abundant and inefficiently used. Over half of the farmers reveal that they use rice husks as source of energy for cooking and heating and 15% burn as waste, unlike rice straw, which they mostly use for feeding animals, discarding or burn in the field. As many farmers are aware of energy valorization practices of the rice by-products, slightly less than half of them express a willingness to adopt them. Biofuel production, detailed analysis of the ash and treatment of the rice husks further revealed its sustainability for energy utilization and increased its acceptance as an alternative energy source.

The low ash and moisture content, together with high content of volatile matter of corn cobs and peanut shells, gave them an advantage over some other biomass for utilization as feedstock to produce solid biofuels. Despite the high ash content of rice husks, it expresses less sintering tendency during high-temperature combustion over peanut shells and corn cobs. The elemental composition of the ash does not present any harm to its utilization as fertilizer on the farm. Mixing rice husks with either peanut shells or corn cobs can improve the energy value of the rice husks and reduce the sintering tendency of peanut shells and corn cobs, thereby avoiding slag formation in the boiler. (The results of the preliminary study of fuel co-blending could be found in the master's Thesis authored by Ohanu Chibueze Franklin (2025), supervised by Alexiou Ivanova T. and Bappah M. On trying to improve the energy value of the studied residual biomass using thermal treatment, torrefaction was discovered to have less effect on biomass with high ash content. Based on the annual production, these three by-products have the potential to serve the energy demand of over eight million Nigerians.

Weight loss of rice husks and corn cobs during decomposition, with respect to temperature, was discovered to be similar. This indicated their similarity in terms of heating rate and decomposition pattern, which is narrower (300 – 500 ºC) compared to peanut shells (300 – 900 ºC). Briquettes produced from peanut shells exhibit higher resistance to abrasion during handling and manipulation, unlike corn cobs briquettes, which may be completely damaged on exposure to handling force. Heating pretreatment, use of binder, smaller particle sizes or varying moisture content can improve the mechanical durability of the briquettes. Rice husk briquettes produce the lowest NO_x and CO emissions during combustion, which were less than the maximum permissible emission in Nigeria. High emission concentrations of biofuel can be associated with the higher content of associated elements in the feedstock itself. It can be minimized by controlling the excess air coefficient.

Utilization of these by-products will provide alternative fuel that can be used as a substitute for firewood and charcoal, which are dominant fuels used for cooking and heating. Similarly, it will reduce deforestation and improve the quality of the environment.

CHAPTER 9 Recommendations, limitations, and future research directions

9.1. Recommendations

1. Subsidize and distribute clean alternatives

For the reduction of overdependence on firewood and charcoal among Nigerian households, government agencies, development partners and concerned organizations should prioritize making alternative energy sources more available and affordable, particularly to low-income and rural households.

2. Scaling up biofuel production from viable by-products

Considering their high calorific values and low ash content, corn cobs and peanut shells should be prioritized for solid biofuel production. Despite having lower energy values, rice husks demonstrate low emissions and are abundant. Their use, especially in blends with peanut shells or corn cobs, should be encouraged to improve combustion properties. Investments in small and medium-scale briquetting technologies are recommended to harness their full energy potential.

3. Briquette quality optimization

Mechanical durability of briquettes can be enhanced through moisture control, appropriate binder selection, size reduction of feedstock and the use of pre-treatment techniques.

4. Promoting clean combustion practices

Adoption of improved cookstoves and user training on airflow control and safe fuel handling to minimize harmful emissions like CO and NOx.

5. Leveraging agricultural waste for energy security

Effective utilization of the studied agricultural by-products could potentially supply cooking energy to over 8 million Nigerians, contributing significantly to Sustainable Development Goals (SDG 7 and SDG 3).

9.2. Limitations

1. Geographic scope

The research is limited to Nigeria and other countries with similar geographical, agricultural and cultural settings.

2. Feedstock scope

The biofuel properties are limited to the three evaluated agricultural by-products, viz. corn cobs, peanut shells and rice husks. Other viable residues, such as cassava peels, sugarcane bagasse and palm kernel shells, were not included.

3. Economic analysis

Economic analysis, such as market feasibility for the adoption of the large-scale biofuel, is not included in the research.

4. Sociocultural factors

The impact of cultural preferences and behavioral resistance to alternative energy adoption was not deeply explored.

9.3. Future Research Directions

1. Field testing and user trials

The direction of future research will focus on pilot testing the produced briquettes in a real household situation for the evaluation of compatibility, performance and acceptance.

2. Techno-economic feasibility

Comprehensive assessment of technical and economic feasibility, including supply chain, production cost, pricing models and return on investment for the scale-up.

3. Exploration of additional feedstocks

Investigation of other available agricultural by-products and considering co-blending among them for better durability and combustion efficiency.

4. Gender and policy integration

Investigating gender roles in household energy decision-making and aligning biofuel adoption strategies with existing energy policies to enhance sustainability.

5. Environmental impact assessment

Life Cycle Assessments (LCA), to determine the net environmental benefits of replacing the use of traditional fuels with advanced alternative biofuels.

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OTHERS

- **Bappah, M**., Bradna, J., Alexiou, T. I. (2023). EVERYTHING MAIZE: FOOD, FEED, OR ENERGY. 10th edition International Scientific-Practical Conference" Education through research for a prosperous society". 10.46727/c.v1.18-19-03-2023. p169-171.

- **Bappah, M**., Alexiou, T. I. (2022). A STUDY OF INVASIVE PLANTS ANDROPOGON GAYANUS AND PENNISETUN PEDICELLATUM FOR RECLAIMING NIGERIAN MINED SITES. Materials of international scientific and advanced conference dedicated to the 100th anniversary of the Dnipro State Agrarian and Economic University (DSAEU) and the 60th anniversary of the scientific school of land reclamation of the DSAEU. pp. 230-233.

- Paramonova, K., Alexiou, T. I., **Bappah, M**. (2023). SOME ASPECTS OF HERACLEUM MANTEGAZZIANUM BIOMASS APPLICABILITY FOR DENSIFIED BIOFUELS PRODUCTION. 10th edition International Scientific-Practical Conference" Education through research for a prosperous society". 10.46727/c.v1.18-19-03-2023. p153-155

Conference contributions

- Oral Presentation: Mechanical durability of briquettes produced from different agricultural by-products. 24th International Workshop for Young Scientists, “BioPhys Spring 2025”, CZU Prague, 29th – 30th May 2025.

- Oral Presentation: Effects of torrefaction on biomass and solid biofuel properties. 5th International Multidisciplinary Conference for Young Researchers "Energy, Sustainability & Society", CZU Prague, October 2024.

- Online Presentation: Everything Maize: food, feed, or energy. 10th edition International Scientific-Practical Conference. “Education through research for a prosperous society”, Moldova 22nd – 24th May 2023.

- Oral Presentation: Agricultural waste biomass as a substitute and sustainable source of energy to fossil fuels. Euroleague for Life Sciences Scientific Student Conference (LLS SSC), CZU Prague. 23rd – 24th September 2022.

- Poster Presentation: Peanut by-product as an energy source for improving peanut productivity. Tropentag, CZU Prague. 13th – 16th September 2022.

- Online Presentation: A study of invasive plants *Andropogon gayanus* and *Pennisetun pedicellatum* for reclaiming Nigerian mined sites. International Scientific and Advanced Conference dedicated to the 100th anniversary of the Dnipro State Agrarian and Economic University (DSAEU) and the 60th anniversary of the Scientific School of Land Reclamation of the DSAEU Dnipro, Ukraine. 23rd – 24th June 2022.

- Participant: Training workshop for Science Teachers in Public Secondary Schools at GGSS Azare. 9th – 12th September 2019.

Author's CV

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Nationality Nigerian

EDUCATION AND QUALIFICATIONS

Ph.D. Sustainable Rural Development In view
Czech University of Life Sciences Prague
Thesis: Assessment of agri residual biomass for energy utilization (case study of Nigeria)

M.Sc. Technology and Environmental Engineering 2019
Czech University of Life Sciences Prague
Thesis: The potential of energy recovery from Biodegradable waste and by-products from small Agricultural farms

Post Graduate Diploma in Education (PGDE) 2013
University of Maiduguri
Thesis: Effect of examination malpractice on the performance of secondary school students (Case study of Katagum Local Government)

B.Eng. Agricultural Engineering 2010
Abubakar Tafawa Balewa University Bauchi
Thesis: Design and construction of a manual citrus fruit juice extractor

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RESEARCH AND WORK EXPERIENCE

09/2021 – Present

Scientific research at the Czech University of Life Sciences Prague
Research on waste management and biofuel production
Biomass characterization tests
Treatment and improvement of biomass properties
Teaching and project activities
Working with data and information

07/2024 – 09/2024 06/2025 – 07/2025	**Intern at Technical University of Moldova (UTM), Chisinau** Use of modern equipment for measuring biomass energy parameters at the laboratory of bioenergy Training on the management practices of greenhouse and hydroponic systems
10/2023 – 11/2023	**Intern at Centre for the Development of Renewable Energy Sources (CEDER), Soria** Testing Energy characterization of biomass
2014 – 2022	**Education officer at Government Day Technical College Azare** Teaching, training and mentoring students Utilization and maintenance of Agricultural tools, implements and machinery Management of the college farm Collaboration with other departments in designing and fabricating simple tools
2013 – 2014	**ABA Nigeria Limited** Accounting Assistant Site Supervision
04/2013 – 12/2013	**Direct Sales Agent at Pension Alliance Limited, Bauchi** Marketing Registration for a retirement savings account. Clients' support services.
2011 – 2012	**College of Education, Azare** National Youth Service Corps Teaching
2008 – 2009	**Intern at Bauchi State Agricultural Development Programme** Technical Support Repair and maintenance of Agricultural machinery. Drilling and installation of irrigation wells

PROJECT PARTICIPATIONS	**Research Projects** **Internal Grant Agency, Faculty of Tropical AgriSciences, CZU Prague**

Appropriate technologies in waste and water management [grant number 20223110].

Appropriate technologies in waste and water management [grant number 20233108].

Appropriate technologies in waste and water management [grant number 20243101].

Waste valorisation for environmental protection [grant number 20253121]

Development Projects

Modernization and raising the prestige of Higher Agricultural Education in Moldova [N. 24-PKVV-004].

Modernization and raising the prestige of Higher Agricultural Education in Moldova" [N. 25-PKVV-005].

Supporting Ukrainian Refugees through Academic Collaboration between Universities in Moldova and the Czech Republic" [N. 25-PKVV-UM-009].

MEMBERSHIPS AND NETWORKS

International Association of Engineers (IAENG – 378109)

Council for the Regulation of Engineering in Nigeria (COREN – R56049)

Teachers Registration Council of Nigeria (TRCN – BA/S/02085)

Young African Leaders Initiative (YALI)

LANGUAGE SKILLS

Mother tongue: Hausa,
Other Languages: English – Proficient
Arabic – Intermediate
Czech – Basic

CERTIFICATIONS

Introduction to Data Science by Simplilearn

Google Data Analytics

Teamwork Foundation with LinkedIn