UNIVERSITI PUTRA MALAYSIA

TECHNO-ECONOMIC VIABILITY ASSESSMENT OF HYBRID BRIQUETTES AS AN ALTERNATIVE DOMESTIC COOKING FUEL FOR RURAL COMMUNITIES IN NIGERIA

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By

KPALO SUNDAY YUSUF

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2021

DEDICATION

This work is dedicated first to my Lord and Saviour, Jesus Christ. Then to my late grandmother Mrs Patricia Comfort Rapu and sister Aisha Yusuf of blessed memory.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Faculty : Forestry and Environment

Growing global demand and utilization of fossil fuels has not only elevated wealth creation, but also increased adverse impacts of climate change from greenhouse gases (GHGs) emissions which endangered public health. In most developing countries including Nigeria, biomass wastes, which include but are not limited to agricultural residues, are produced in large quantities annually. They are either inefficiently used or disposed of indiscriminately, which threatens the environment. However, there is a way to deal with this situation which is by converting these biomass wastes, through densification, into high-density and energy-efficient briquettes. Densification of biomass into briquettes presents a renewable energy option as an alternative to fossil fuels. This dissertation reports the findings of technical and economic viability assessment of hybrid briquettes developed from a blend of corncobs (CC) and oil palm trunk bark (OPTB) under a low-pressure densification technique. The raw materials were chopped into small pieces and then sun-dried to reduce the moisture content. A grinding machine was used to grind the dried raw materials further and then sieved to obtain the desired particle size of ≤2 mm. The individual materials (corncobs and OPTB) and mixed materials (blend of both) were measured into 1000 g portions and wastepaper pulp (100 g) was added to each mixture as a binder. A total of five different mixtures with distinct identities (namely CC, MIX 1, MIX 2, MIX 3, and OPTB) were formulated according to the quantities of corncobs to OPTB. Briquettes were produced using a manually operated 20-tonne hydraulic piston press in a laboratory at 28°C temperature and ≤7 MPa compaction pressure. The quality of the briquettes was determined in terms of physical, mechanical and thermal properties while the performance of the briquettes in a cooking application was determined by a water boiling test. Additionally, the economic feasibility of the hybrid briquette production from a household point of view was determined by a financial model using specific cost-benefit analysis tool.

The study revealed that the physical properties of hybrid briquettes ranged from 9.24–10.00% moisture content, 0.38–0.40 g/cm^3 density, and 87.60%–92.00% water resistance. Mechanical strength was 98.28%–99.08% shatter index and 18.47–21.75 Mpa compressive strength, while calorific values ranged from 16.54–16.91 MJ/kg. Results also showed that the volatile matter, ash content and calorific value increased with the increase in OPTB in the ratios while the fixed carbon decreased. Water boiling test results showed that hybrid briquettes (MIX 2 and MIX 3) were similar in values based on time taken to ignite briquettes and boil 1 L of water (17.54 min and 17.13 min), fuel burning rate (0.69 kg/h and 0.70 kg/h) and specific fuel consumption (0.16 kg/liter and 0.15 kg/liter). However, MIX 2 performed better in terms of thermal fuel efficiency (17.25%) and produced less quantity of ash during combustion and thus, considered the optimum combination and was chosen for economic evaluation. CO_2 emission of all briquettes ranged from 241-281 gCO_2e. Economic evaluation of hybrid briquettes showed that it took a minimum of \$0.16 to produce 1 kg of hybrid briquettes. On the assumption that it can sell for \$0.26 per kg, an annual revenue of \$3,637.69 and a net profit of \$1,438.69 will be derived. Furthermore, economic feasibility indicators showed that net present value (NPV) was \$6,755.91, payback period (PBP) was 2.40 years, internal rate of return (IRR) was 48.8% and benefit cost ratio (BCR) was 1.43. An accounting profit can be achieved as long as briquette sales are above the break-even point of 7,329.8 kg.

Sensitivity analysis showed that the risk of a significant reduction in NPV was from operation and maintenance cost, and lower briquettes' selling price. Households could save about 25% from their per-capita expenditure on fuelwood when briquettes are utilized. Overall, it can be inferred that developing briquettes from corncobs and OPTB was technically and economically feasible. The hybrid briquettes are environmentally friendly, cost effective and affordable compared to fuelwood and fossil fuel as alternatives for domestic cooking purposes. They can complement domestic cooking fuels like firewood, charcoal and kerosene, thus decreasing the high demand for such fuels. The addition of briquettes to the energy mix will help to diversify the sources of energy in Nigeria and therefore help to improve the energy security in line with the nation's energy policy. Adopting briquetting technology will increase access to clean and affordable energy in line with the 7th goal of the United Nation's Sustainable Development Goals.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN KELAYAKAN TEKNIK-EKONOMI BRIQUETT HYBRID SEBAGAI BAHAN MEMASAK DOMESTIK ALTERNATIF UNTUK MASYARAKAT PERDANA DI NIGERIA

Oleh

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Permintaan global yang semakin meningkat dan penggunaan bahan bakar fosil bukan sahaja meningkatkan ekonomi tetapi mengakibatkan kesan buruk kepada perubahan iklim disebabkan pelepasan gas rumah hijau (GHG) yang boleh membahayakan kesihatan penduduk setempat. Di kebanyakan negara membangun termasuk Nigeria, sisa biojisim, yang merangkumi sisa pertanian, dihasilkan dalam jumlah besar setiap tahun. Ianya digunakan secara tidak efisen atau dibuang begitu sahaja, yang membahayakan alam sekitar. Bagaimanapun, ada cara lain untuk menghadapi situasi ini, iaitu dengan menukarkan sisa biojisim kepada briket melalui proses pemadatan, bagi menghasilkan briket yang berketumpatan tinggi dengan peningkatan efisiensi tenaga. Pemadatan biojisim kepada briket boleh dijadikan sebagai pilihan tenaga boleh diperbaharui sebagai bahan alternatif kepada bahan bakar fosil. Disertasi ini melaporkan penemuan briket hibrid yang dihasilkan daripada campuran tongkol jagung (CC) dan kulit batang kelapa sawit (OPTB) di bawah teknik pemadatan dengan tekanan yang rendah secara teknikal perlaksanaannya dan lebih ekonomik. Bahan mentah dicincang untuk menghasilkan kepingan kecil dan dikeringkan di bawah sinar matahari bagi mengurangkan kadar kelembapan. Mesin pengisar digunakan untuk mengisar bahan mentah kering dengan lebih halus dan kemudian diayak untuk mendapatkan ukuran zarah yang dikehendaki iaitu $\leq$2 mm. Bahan-bahan individu (tongkol jagung dan OPTB) dan bahan campuran (campuran keduanya) diukur supaya dijadikan 1000 g dan ditambah dengan 100g pulpa kertas buangan pada campuran ini sebagai pengikat. Sebanyak lima campuran berbeza dengan identiti yang berbeza (iaitu CC, MIX 1, MIX 2, MIX 3, dan OPTB) dirumuskan mengikut nisbah kuantiti tongkol jagung ke OPTB. Briket dihasilkan dengan menggunakan mesin piston tekan hidraulik 20 tan pada suhu 28 °C dan tekanan pemadatan $\leq$7 MPa, yang dikendalikan secara manual di makmal. Kualiti briket ditentukan dari segi fizikal, mekanikal dan termal sementara prestasi briket dalam aplikasi memasak ditentukan melalui ujian air mendidih. Tambahan pula, ekonomi pengeluaran briket dari sudut isi rumah ditentukan dengan model kewangan menggunakan kaedah analisis kos-manfaat.

Kajian ini menunjukkan bahawa sifat fizikal briket hibrid berkisar mempunyai kandungan kelembapan antara 9.24-10.00%, ketumpatan antara 0.38–0.40 g/cm3, dan 87.60% –92.00% kalis air. Kekuatan mekanikal menunjukkan indeks pemecah antara julat 98.28% –99.08% dan kekuatan mampatan antara 18.47–21.75 MPa, sementara nilai kalori berkisar antara 16.54–16.91 MJ/kg. Hasil kajian juga menunjukkan bahawa bahan meruap, kandungan abu dan nilai kalori meningkat dengan peningkatan OPTB dalam nisbah, sementara karbon tetap menurun. Hasil ujian air mendidih menunjukkan bahawa briket hibrid (MIX 2 dan MIX 3) mempunyai kesamaan berdasarkan kepada masa yang diambil untuk menyalakan briket dan mendidihkan 1 L air (17.54 min dan 17.13 min), kadar pembakaran bahan bakar (0.69 kg /h dan 0.70 kg /h) dan penggunaan bahan bakar tertentu (0.16 kg / liter dan 0.15 kg / liter). Walau bagaimanapun, MIX 2 menunjukkan prestasi yang lebih baik dari segi kecekapan bahan api (17.25%) dan menghasilkan kuantiti abu yang sedikit semasa pembakaran dan dengan itu, dianggap sebagai kombinasi yang optimum dan dipilih untuk penilaian ekonomi.

Pelepasan CO2 bagi kesemua briket berkisar di antara 241-281 gCO2e. Penilaian ekonomi untuk briket hibrid ini menunjukkan bahawa kos minimum sebanyak ($0.16) diperlukan untuk menghasilkan 1 kg briket hibrid. Dengan andaian bahawa ianya dapat dijual dengan harga sebanyak $ 0.26 per kg, hasil tahunan sejumlah $ 3.637.69 dan keuntungan bersih sebanyak $ 1.438.69 akan diperoleh. Tambahan pula, petunjuk ekonomi menunjukkan bahawa nilai kini bersih (NPV) adalah sebanyak $ 6.755.91, tempoh pembayaran balik (PBP) adalah selama 2.40 tahun, kadar pulangan dalaman (IRR) adalah 48.8% dan nisbah kos manfaat (BCR) adalah 1.43. Keuntungan perakaunan dapat dicapai selagi penjualan briket berada di atas tahap titik pulang modal sebanyak 7,329.8 kg.

Analisis kepekaan menunjukkan bahawa risiko penurunan ketara dalam NPV adalah daripada kos operasi dan penyelenggaraan, dan harga jual briket yang lebih rendah. Keperluan rumah tangga dapat dijimatkan sebanyak 25% dari pengeluaran per kapita apabila penggunaan kayu bakar digantikan dengan briket. Secara keseluruhan, dapat disimpulkan bahawa penghasilan briket hibrid dari tongkol jagung dan OPTB secara teknikal perlaksanaannya adalah lebih ekonomik. Briket hibrid adalah lebih mesra alam, merupakan harga yang berpatutan dan lebih menjimatkan jika dibandingkan dengan kayu bakar dan bahan bakar fosil, yang boleh digunakan sebagai bahan alternatif bagi tujuan masakan domestik. Penerimaan teknologi briket akan dapat meningkatkan penggunaan kepada tenaga bersih dan mampu milik sejajar dengan matlamat ke-7, Pembangunan Lestari Pertubuhan Bangsa-Bangsa Bersatu.

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This thesis was submitted to the Senate of the Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
ASTM	American standards and testing material
BCR	Benefit Cost Ratio
BEP	Break-even point
CC	Corncobs
CO_2	Carbondioxide
CO_{2e}	Carbondioxide equivalent
d.b	Dry basis
DMRT	Duncan Multiple range Test
ECN	Energy commission of Nigeria
FBR	Fuel burning rate
g/cm^3	Gram per centimetre cube
GHG	Greenhouse gases
IRR	Internal Rate of Return
ISO	International Standards Organization
Kg/h	Kilogram per hour
Kg/liter	Kilogram per liter
kWh	Kilowatt hour
L	Liter
LPG	Liquefied petroleum gas
MJ/kg	Megajoules per kilogram
MPa	Megapascal
mm	Millimetre

₦	Nigerian Naira
NBS	National Bureau of Statistics Price watch
NEP	National energy policy
NERC	Nigerian Electricity Regulatory Commission
NSIWC	National Salaries, Incomes and Wages Commission
NPV	Net Present Value.
OPT	Oil palm trunk
OPTB	Oil palm trunk bark
O&M	Operating and maintenance
PBP	Payback Period
PMS	Premium motor spirit
POS	Palm oil shell
PPPRA	Petroleum Products Pricing Regulatory Agency
RE	Renewable energy
REMP	Renewable energy master plan
SDG	Sustainable development goal
SFC	Specific fuel consumption.
TFE	Thermal fuel efficiency
USD	United States Dollars
w.b	Wet basis
$	Dollars (USA)

CHAPTER 1

INTRODUCTION

1.1 Background of the study

The demand for energy has been on the increase mostly attributed to the growth in human population as well as a significant rise in the commercial and industrial activities witnessed across the globe. Fossil fuels such as petroleum products, coal, natural gas, etc. are the most important energy sources which supplies about 80% of the global primary energy requirement (Sansaniwal et al., 2017). The depletion of fossil fuel, which is non-renewable has been a global issue, nevertheless, it is the growing utilization that is currently presenting a new and major challenge.

According to Tursi, (2019), the increasing usage of fossil fuels for industrial and post-industrial development has attracted growth in wealth, but so also higher levels of pollution and the consequent degeneration of public health. In 2018, the global carbon dioxide (CO_2) emissions from fuel combustion reached 32.8 billion tonnes (International Energy Agency, 2019a). The rise of carbon dioxide concentrations will continue unless emissions are drastically reduced. A recent report noted that the earth is set to warm up to 3.2°C by 2100 unless efforts to cut emission are tripled (UNEP, 2019). The desire for the average rise in temperature to be sustained well below 2°C requires a total decarbonisation of energy generation away from fossil fuels (Watts et al., 2018).

Interestingly, fossil fuels are not the only constituents of environmental degradation. Inefficient use and disposal of biomass as well as inadequate proper cooking technologies also persist. Of all energy sources, biomass is the third largest energy resource in the world (Tumuluru et al, 2011). Biomass is organic and a renewable energy source. It is one of humanity's earliest sources of energy particularly in rural areas where it is often the only accessible and affordable source (Demirbas, 2004). It is also the most dominant source of cooking and heating energy for three quarters of all people in developing countries, and accounts for about 14% of the total global energy use (Geyer and Iriarte, 2007, Kumar and Singh, 2017, Baqir et al, 2018).

In most of these countries, more than 80% contributes to national energy consumption (Cherubini et al., 2009, IEA, 2010). In Ethiopia for instance, traditional biomass burning supplies more than 92% of its energy consumption (Asresu, 2017), over 64% in Ghana (Ahiataku-togobo and Ofosu-Ahenkorah, 2009), 70% in Kenya (Mwakubo et al, 2007), 60% in Bangladesh (Rahman et al, 2018), 7% to electricity in Brazil (WEO, 2006, Ribeiro and Rode, 2016) and 78% in Nigeria (Agbro and Ogie, 2012),.

Nigeria is a major producer of agricultural products with an abundance of agricultural residues. These could be used for energy production to decrease the amount of fuelwood requirement for daily cooking. Corncobs and oil palm trunk (OPT) are agricultural waste readily available in Nigeria and are the focus of this study. Beside their availability, they are so chosen for the energy potential they possess based on analysis. Biomass, especially agricultural residue, is a renewable energy resource. However, it must be converted into a ready-to-use, high-energy resource in order to be considered as viable fuel (Mendoza-Martinez et al., 2019). Biomass densification, also known as briquetting, offers a unique opportunity of converting biomass wastes with poor energy characteristics into solid fuels with high energy concentration. Additionally, densification increases bulk density thereby optimizing transport and enabling the use of biofuel in areas far from where waste is generated. In turn, the necessary homogeneity is achieved

Studies have shown that corncobs are good for briquettes production. However, it has been observed that corncob briquettes have tendency to absorb water due to high particle porosity (Muazu and Stegemann, 2015). They also displayed inadequate durability for handling and transporting after densification using low compaction pressure at room temperature (Kaliyan and Morey, 2010, Mitchual et al., 2013a). OPT on the other hand has the potential to serve as a good feedstock for biofuel production based on ultimate and proximate analysis including the calorific value (Abnisa et al., 2013, Loh, 2017). Presence of ash content is its major demerit which corncob with lower ash is envisaged to complement. Additionally, studies on briquette production using OPT solely or mixed with other residues are scarce until now. Previous studies have confirmed that combination of different biomass materials enhances the quality characteristics of densified products (Mitchual et al., 2013, Harun et al., 2018, Mitchual et al., 2019).

Briquetting can be done with little amount of energy using low compaction pressure. Briquettes produced under lower pressure technique have been reported to easily fall apart while those under high pressure remained durable (Mitchual et al., 2013a), However, compaction pressure of ≤7Mpa has been used to produce low-cost briquettes that are durable (Bazargan et al., 2014, Yank et al., 2016, Lubwama and Yiga, 2017). These researchers used binding agents which is a requirement for low pressure densification. The purpose of the binder was to enable agglomeration of the material. Resource problems from the use of food product such as starch as binders (Muazu and Stegemann, 2017) may arise, so non-edible and available products like waste paper, turned into pulp, can be used as alternatives.

1.2 Research problem

In Nigeria, the majority of energy used mostly for cooking at household level is primarily derived from biomass (67% fuelwood, 6% charcoal) and fossil fuel (18% coal and kerosene) (International Energy Agency, 2019b). Other energy sources such as liquefied petroleum gas (LPG) (5%) and electricity (4%) are expensive for many Nigerians and grossly inadequate in supply even where they are available (Emerhi, 2011). Majority of Nigerians especially rural dwellers depend on fuelwood for cooking and heating. Figure

1.1 shows the percentage of households that depend on fuelwood for cooking by regions in Nigeria. Fuelwood is generated from the forest as an energy source and is consumed either directly by burning in open fires or by converting to charcoal before use. Indiscriminate harvesting of wood, open burning and charcoal production are all inefficient and unsustainable leading to several environmental problems such as deforestation, soil erosion, land degradation and air pollution from emission of greenhouse gases.

According to Shaaban and Petinrin (2014), about 350,000 hectares of forest and natural vegetation are lost annually with a much lower afforestation rate of 50,000 hectares per annum. The consequences of deforestation are so massive that between 1990 and 2005, Nigeria has lost a staggering 79% of its old-growth forests (Mfon et al., 2014). Also, Bolaji, (2012) reported that fuelwood, roots, agricultural residues and animal dung all produce high emissions of carbon monoxide, hydrocarbons and particulate matter

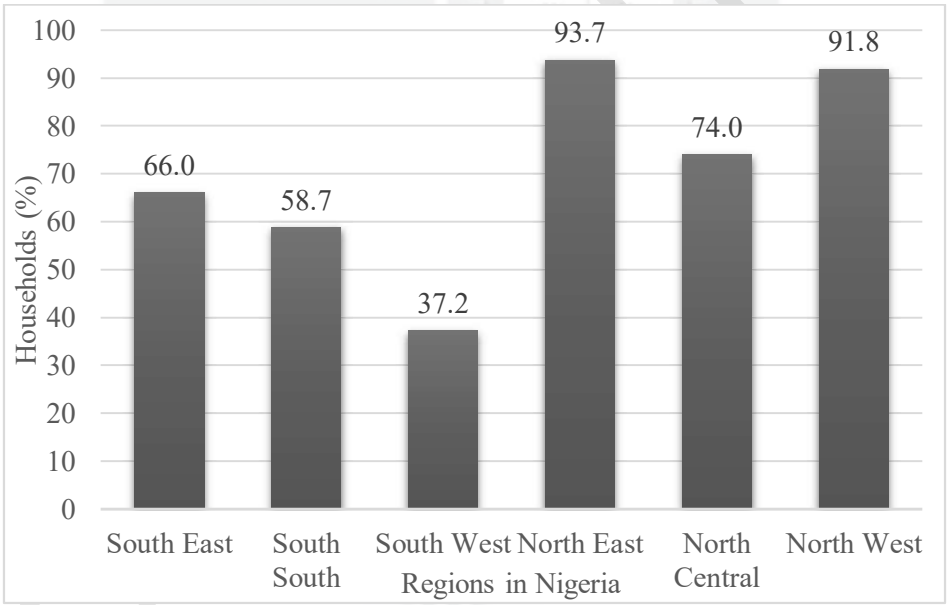

Figure 1.1 : Households dependent on firewood for cooking by regions in Nigeria
(Source: Sa'ad and Bugaje, 2016)

Additionally, domestic cooking is a laborious task particularly in many rural communities. With the depleting natural wood reserves, it is a common practice for women and children to trek as far as 6 km or spend more than 6 hours each day collecting and preparing fuelwood in order to prepare meals (Kuhe et al., 2013, Obi et al., 2014). The search for fuelwood results into low production in agriculture, low incomes and household food insecurity (Katimbo et al., 2014). When it is eventually found, cooking is usually done on a traditional "three stone" fuel wood stove (Gujba et al., 2015) either in the open or in a poorly ventilated kitchen. Such cooking method

exposes women and children to adverse effects of indoor air pollution from incomplete combustion. They are likely to suffer from elevated blood pressure which leads to increased risk of stroke, kidney and cardiovascular diseases (Weinhold, 2011), including pneumonia amongst children of less than five years of age (Barnes, 2014). Recently, between 106,900 to 605,100 deaths were recorded from indoor air pollution caused by biomass burning in Nigeria (Balmes, 2019)

Generally, the cost of energy in Nigeria has been on the increase for the past 20 years. For instance, the pump price of premium motor spirit (PMS) otherwise known as petrol moved from $0.07/l in 2002 to $0.25/l in 2012 (BBC). Electricity tariff rose from $0.02/kWh to $0.03/kWh within the same period (Tallapragada, 2009). Just recently, the Federal Government of Nigeria through its regulatory agencies announced the increment in the pump price of petrol and electricity tariff again. The pump price of petrol was increased from $0.38/l to $0.40/l (PPPRA) while electricity tariff has been raised from $0.08/kWh to as much as $0.16/kWh (NERC). At present, the average price of LPG is $10.80 for a 12.5 kg gas cylinder while kerosene is $0.91/l (NBS).

Based on a market survey using direct communication with vendors, current prices of charcoal and fuelwood are $0.52 and $0.26 per kg respectively depending on location. Apart from petrol that has been subsidized until now, there is neither subsidy nor any incentive given for the consumption of these fuels including electricity. The rising cost of petroleum products and erratic electricity supply has made the use of fuelwood inevitable and a significant source of energy for households and small to medium businesses (Lamido et al., 2018).

The need to replace these resources especially fuelwood with an alternative that is cheaper, cost-effective and environmentally friendly for rural dwellers will be a welcome idea. Even with the potentials of corncobs and OPT to produce bio-energy, the residues are mostly left to rot on farmlands encouraging emission of methane or cleared and burnt openly in readiness for the next planting season (Olorunnisola, 2007). Additionally, where they are not abandoned or burnt, they are used as alternative to charcoal and fuelwood for domestic cooking purposes, particularly in the rural areas. Generally, such biomass displays poor energy characteristics when used in their natural state (Felfli et al., 2011, Araújo et al., 2016). They also show low bulk densities due to their porous structure which makes processing, shipping, storage, and combustion difficult (Sepúlveda et al., 2018). Both methods of utilization of the residues in raw form and disposal by open burning or allowing to rot on farmlands are inefficient and thus, cause environmental pollution.

Briquetting technology is an appropriate means of converting biomass residue into solid fuel for domestic cooking in rural areas. Densification of corncobs and OPT as alternative sources of energy is desirable because it could tackle problems of waste disposal, energy shortages as well as mitigate against indoor air pollution. Given that the briquette technology is not popular in Nigeria, the lack of adequate technical know-how, high investment cost from high energy input to the process which could result in high

production cost may mitigate against the production of briquettes. This called for an empirical research to find answer to a fundamental question. Thus, how technically and economically viable is a household scale hybrid briquette production from a blend of corncob OPT waste for application in rural communities in Nigeria? The potential energy content and generation in large quantity presents corncobs and OPT as sustainable feedstock. This study anticipated that combining these materials will result in quality hybrid briquettes that will not only contribute to alleviating energy poverty but also to a more sustainable waste management strategy in Nigeria.

1.3 Research questions

In furtherance to the fundamental question that this research sought to address, it also focused on answering the following questions.

1. Can a blend of corncobs and the bark oil palm trunk be densified into hybrid briquettes?
2. What is the quality of the hybrid briquettes in terms of physical, mechanical and thermal properties?
3. How will the developed hybrid briquettes perform in a domestic cooking application? How long will it take for the hybrid briquettes to ignite and boil water?
4. How much will it cost to produce the hybrid briquettes using a low-pressure densification technique?
5. How economically viable will this technology be for application in rural communities of the study area?

1.4 Research objectives

The overall aim of the study is to assess the technical and economic viability of converting corncobs and oil palm trunk waste into hybrid briquettes as an alternative energy source for cooking applications in rural communities in Nigeria.

The specific objectives of the research are the following:

1. To characterize the briquettes produced from corncob, OPTB and their mixtures for their physical, mechanical and thermal properties.
2. To determine the fuel performance and combustion behaviour of the briquettes
3. To assess the technical and economic feasibility of a household briquettes production from corncob and OPTB in Nigeria.

1.5 Significance of the study

This study is significant in a number of ways. Generally, it would contribute to the existing body of knowledge on the densification of biomass materials in Nigeria. Those to benefit in this respect include researchers, and other stakeholders.

In specific terms, the findings would extend the knowledge in producing briquettes from corncobs and most importantly highlight the potential of oil palm trunk which hitherto has not been used in briquette production. This study provides a piece of baseline information on the economic viability of briquette production on a household scale for socio-economic benefits to rural communities of Nigeria. Rural communities that experience lack of electricity will be availed with the knowledge of a simple technology for producing briquettes as alternative energy source. As briquettes can serve as alternative energy source for domestic application, the usage of firewood and charcoal will be reduced and thus, putting less pressure on our forests. The time and distance taken by women and children to seek for fuelwood before preparing a meal will be reduced leading to energy savings.

The outcome of this study will showcase the possibility of generating employment for rural dwellers where these residues are available. The use of briquettes will curtail GHG emissions from fossil fuels and prevent the exposure of women and children to adverse effects of indoor air pollution from incomplete combustion of traditional biomass fuels. Women and young children, who spend numerous hours in the kitchen, will be the most beneficiaries of briquettes being a cleaner cooking fuel. The addition of briquettes to the energy mix will help to diversify the sources of energy in Nigeria and therefore help to improve the energy security in Nigeria.

1.6 Scope and limitation of the study

In this research, the raw materials used for the development of the fuel briquettes were corncobs and OPTB. These materials were chosen because of their availability in large quantity and their energy potential. The densification of the biomass materials was experimentally done in a laboratory and manually based on a low-pressure technique. The evaluation of the hybrid briquettes was with reference to their technical and economic viability. The technical viability covers evaluation of quality (physical, mechanical and thermal properties) and performance and combustion behaviour (time taken to ignite briquette and boil water, thermal fuel efficiency, fuel burning rate, specific fuel consumption and gaseous emission), while the economic viability covered the evaluation of costs and feasibility. Additionally, economic feasibility study was limited to the level of a household scale briquette production.

The limitation of the study included the inability to carbonize the raw material to make comparison between carbonized and non-carbonized briquettes. The micro-structural analysis of the developed briquette and its relationship with the formation of bonds could

not be examined because of lack analytical of equipment. Additionally, time was not available for a survey on consumer perception and willingness to adopt this cooking fuel including a market survey on how the briquettes supply and demand could be met.

1.7 Thesis organization

Chapter 1 introduced and presented the background of the study. Other aspect included in this section are the statement of the research problem, research aim and objectives and the significance of the study among others.

Chapter 2: contained information on renewable energy resources and policies in Nigeria. It also provided a detailed review of the technical and economic aspects of biomass briquetting. Specific reference was made to the biomass resources, feedstock pre-processing, briquetting process parameters, briquetting technology and briquettes quality evaluation parameters. The review also includes economic aspect of briquetting relating to costs and feasibility.

Chapter 3 describes extensively the methodology used in the preparation of materials and production of briquettes. This section further describes the methods applied in determining the quality, performance, costing and economic feasibility of the produced briquettes. Finally, the chapter reported a detailed explanation on the data analysis.

Chapter 4 presents the results and discussion of the experimental study. Physical, mechanical and thermal qualities which describes the quality of briquettes were assessed. The performance of the briquettes in a cooking application was assessed based on result from a water boiling test. The chapter also presented results of economic evaluation which provided information on the economic viability of the briquette production.

Chapter 5 contains the summary and conclusions of findings from the research based on the set objectives. Furthermore, recommendations were made to address the issues arising and areas of further research were suggested.

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LIST OF PUBLICATIONS

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Kpalo, S Y, & Zainuddin, M. F. (2020). Briquettes from Agricultural Residues. An Alternative Clean and Sustainable Fuel for Domestic Cooking in Nasarawa State, Nigeria. *Energy and Power*, *10*(2), 40–47. https://doi.org/10.5923/j.ep.20201002.03

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