VALORIZATION OF UNDERUTILIZED LIGNOCELLULOSIC BIOMASS WASTES FOR BIOFUEL PRODUCTION

A PHD DISSERTATION PRESENTED TO THE DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING (MSE)

AFRICAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

BY

UZOAGBA, CHIDIEBELE EJIKEME JOSEPH

(70235)

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In Partial Fulfilment of the Requirements for the Degree of
Doctor of Philosophy (Ph.D.) Degree

By

Uzoagba Chidiebele Ejikeme Joseph
(70235)

Abuja, Nigeria

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CERTIFICATION

This is to certify that the thesis titled "**VALORIZATION OF UNDERUTILIZED LIGNOCELLULOSIC BIOMASS WASTES FOR BIOFUEL PRODUCTION**" submitted to the School of Postgraduate Studies, African University of Science and Technology (AUST), Abuja, Nigeria for the award of the Doctoral degree is a record of original research carried out by Uzoagba, Chidiebele Ejikeme Joseph in the Department of Materials Science and Engineering (MSE).

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UZOAGBA, CHIDIEBELE EJIKEME JOSEPH
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A THESIS APPROVED BY THE MATERIALS SCIENCE AND ENGINEERING DEPARTMENT

AFRICAN UNIVERSITY OF SCIENCE AND TECHNOLOGY (AUST) – ABUJA, NIGERIA.

PHD COMMITTEE MEMBERS:

Prof. Edmund C. Okoroigwe (University of Nigeria, Nsukka)

Prof. Helena Pereira (University of Lisbon, Portugal)

Dr. Vitalis C. Anye (African University of Science and Technology, Nigeria)

Dr. Abdulhakeem Bello (African University of Science and Technology, Nigeria)

Dr. Marzieh Kadivar (University of Sao Paulo, Brazil)

RECOMMENDED:

____

SUPERVISOR, PROFESSOR AZIKIWE PETER ONWUALU, FAS

APPROVED: ____

HEAD, DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

____

CHIEF ACADEMIC OFFICER

ABSTRACT

The study focuses on utilizing lignocellulose biomass (LCB) as a sustainable feedstock for biofuel production to address fossil fuel depletion, climate change, energy poverty, and environmental issues in Africa. With global energy demand rising and agriculture generating significant waste, the study explores agricultural residues and unconventional biomass sources, such as *Prosopis africana*, for bioenergy generation. Africa faces severe energy poverty, with millions lacking access to electricity and clean cooking facilities. The research aims to assess the energy potential of these residues and promote circular economy principles through bioenergy production. Methodologically, the study used data from the FAOSTAT database to analyze various crop residues for their suitability in bioenergy generation. It employed empirical analysis and modeling techniques to assess energy potential. For *Prosopis africana*, proximate, ultimate, and compositional analyses were performed using advanced techniques like scanning electron microscopy, X-Ray diffraction, and thermogravimetric analysis to determine the biomass's physical, thermal, and chemical properties. Additionally, the hybrid composition of *Prosopis africana* pod and cowpea husk was evaluated for briquette production, optimizing particle size, binder concentration, and densification pressure using Response Surface Methodology. Results indicate that agricultural residues hold significant potential for bioenergy, supporting sustainable resource utilization and promoting circular economy practices. *Prosopis africana* exhibited high heating values (15.23 to 20.49 MJ/kg), positioning it as a strong candidate for biofuel production. Optimal briquette properties were achieved with specific particle size, binder concentration, and densification pressure, improving mechanical and combustion characteristics. The study concludes that agricultural residues and *Prosopis africana* can alleviate Africa's energy challenges, promote environmental sustainability, and contribute to economic development. The findings offer critical insights into scaling bioenergy production and adopting circular economy principles. Further investigations are ongoing to address socio-economic challenges related to bioenergy adoption.

DEDICATION

This doctoral research is dedicated first to God Almighty, as gratitude for life, provisions, and protections. His amazing grace exemplified in my children, Chimalijem (He knows my journey) my first daughter; Chizulum (He is sufficient for me) my second daughter; and my lovely wife, Chinenye (He continues to do new things for me) has kept me going.

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ABBREVIATIONS

PA	*Prosopis africana*
XRD	X-ray Diffraction
TGA	Thermogravimetric Analyses
CCUS	Carbon Capture, Utilization and Sequestrations
EE	Energy Efficiency
REA	Rural Electrification Agency
FTIR	Fourier Transform Infrared Spectroscopy
GHGs	Greenhouse Gases
TGA	Thermogravimetric Analyses
CHNS/O	Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen
DP	Densification Pressure
SFC	Specific Fuel Consumption
NETs	Negative Emissions Technologies
FTIR	Fourier Transform Infra-Red Spectroscopy
MToe	Million Tonnes Oil Equivalent
PAP	Prosopis Africana Pods
CPH	Cowpea Husks
CHP	Combined Heat and Power
SSA	Sub-Sahara Africa
RPR	Residue-to-Product Ratio
Rf	Recoverability Factor
LHV	Lower Heating Value
HHV	Higher Heating Value
RSM	Response Surface Methodology
IEA	International Energy Agency
CO_2	Carbon (iv) oxide
LCB	Lignocellulose Biomass

CHAPTER ONE

INTRODUCTION

1.1 Background

In a business-as-usual scenario, greenhouse gas (GHG) emissions will continue to increase, causing the global average temperature to continue to rise [1]. This will consequently lead to ice melting in the polar regions and an increase in sea levels. Reaching the 1.5 °C target of the Paris Agreement is crucial to prevent the worst impacts of climate change [2]. Being ambitious with emission reductions is critical to keeping our planet within livable limits of warming. The global energy sector's transition to net-zero carbon emissions by 2050 will require a complete transformation of how we produce, transport, and consume energy. However, the deployment of clean energy like biofuels (solid, liquid, and gases) will play a huge role in the decarbonization of economies.

In recent times, the whole world has been responding to climate actions to keep the global average temperature rise below 1.5 °C with more focus and emphasis on Negative Emissions Technologies (NETs) [3] or Greenhouse Gas Removal (GGR) technologies [4] to remove greenhouse gases (GHGs) from the atmosphere and sequester them. One such technology is bioenergy with carbon capture and storage (BECCS) [5] among others like direct-air capture (DAC), carbon mineralization, geologic sequestration, terrestrial carbon removal and sequestration, and blue carbon [6]. Coupling bioenergy production with carbon capture and sequestration can lead to net negative emissions as carbon stored by photosynthesizing biomass growth is valorized or sequestered rather than released to the atmosphere as seen in **Fig. 1.**

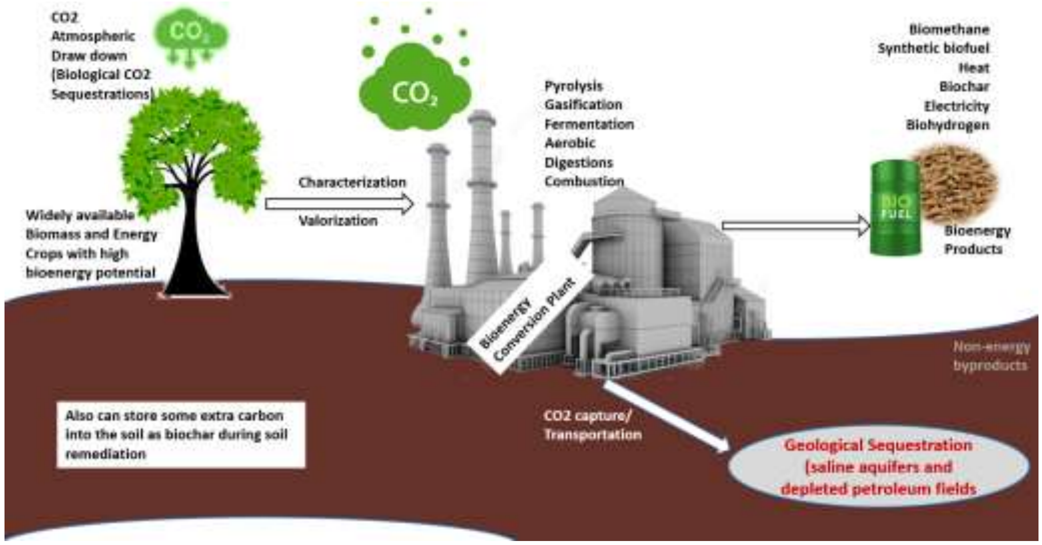

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Fig. 1: Valorization of biomass material source

The Intergovernmental Panel on Climate Change (IPCC) has estimated that to limit the average global warming to 1.5 °C, biomass energy utilization coupled with carbon capture and sequestration has two-thirds chances of removing 12 Giga tonnes of CO_2 annually which amounts to 25 % of current emissions, with forestry, agriculture, and land-use related net emission techniques projected to remove 1 to 5 Giga tonnes of CO_2 per year in 2100. These would require 25 % to 80 % of the global agricultural land amounting to 0.4 and 1.2 billion hectares of land [7], [8]. Hence there is need to also make use of current biomass wastes for bioenergy applications and it starts with a scientific characterization of the biomass for bioenergy and other bio-product applications.

Transiting from fossil fuels to renewables like biofuels would require continuous and sustainable improvement in the production and efficiency of the biofuels, especially the solid fuels (such as fuel briquettes) through for example, densification for better heating efficiency and easier transportability [9]. The size of the particles of the fuel briquettes also improves the fuel characteristics as one of the renewable energies [10], [11], [12]. Also, prior to densification for fuel briquetting which improves the thermal properties, transportability, labour cost reduction [13], raw material sourcing, collection, pretreatment, preparation, , and pulverization are required. The densification in any form or shape could be done with or without a binding agent but significantly under high pressure for better energy per volume [14]. Densified briquettes have shown about one-fifth increase in combustion properties, and one-ninth in GHG emissions reductions when compared to coal [15].

There are still rare studies on the combined effect of particle size, binding agent proportions, feedstock composition, and densification pressure in fuel briquette production. The *Prosopis africana* (PA) wastes, also known as the African Mesquite, has never been valorized as a briquette despite its abundance in Africa and some other parts of the world. However, cowpea husks (CPH) and Cassava starch have been used in the past. These raw materials are in abundance in sub-Saharan Africa (SSA), especially Nigeria, and hence present huge commercial potential for fuel briquettes. Different forms of biomass, such as forest residues, and agro wastes, can be an environmentally friendly alternative to fossil fuels and raw materials. It can also be used as a raw material in the chemicals and materials industry. It is estimated that biomass has the potential to provide 23 % to 50 % of the world's energy needs [16]. It is particularly suited to be used as a raw material for heavy fuels for marine and aircraft propulsion and as a base material for the chemicals industry.

Biomass valorization can generate jobs and economic opportunities in rural areas. It aids in curbing greenhouse gas emissions and fostering sustainable development of the environment among others. Its valorization offers opportunities for advancing rural electrification in any developing country. One method involves establishing small-scale biomass power plants in a rural area, utilizing locally available biomass like agricultural waste and wood chips [17]. The significance of biomass energy (bioenergy) is growing, making it a crucial element in the global future energy landscape. Harnessing biomass valorization for energy is critical in advancing rural electrification in developing countries [18]. It offers a renewable, locally abundant, and sustainable energy source, fostering job creation and economic opportunities in rural regions. To realize the potential benefits of bioenergy, there is a requirement for policies and incentives that encourage the adoption of biomass valorization technologies and facilitate the growth of a biomass-based energy sector. **Fig. 2** shows diverse sources of biomass waste, each with its unique composition and potential for energy recovery or other valuable applications. Residues like crop residues (stalks, leaves, husks), straw (rice, wheat, barley), bagasse (from sugarcane), corn cobs, and stover are generated from agricultural production, manure (from livestock such as cows, pigs, poultry), poultry litter, fish wastes are generated from animal wastes while aquatic biomass is from algae and aquatic plants.

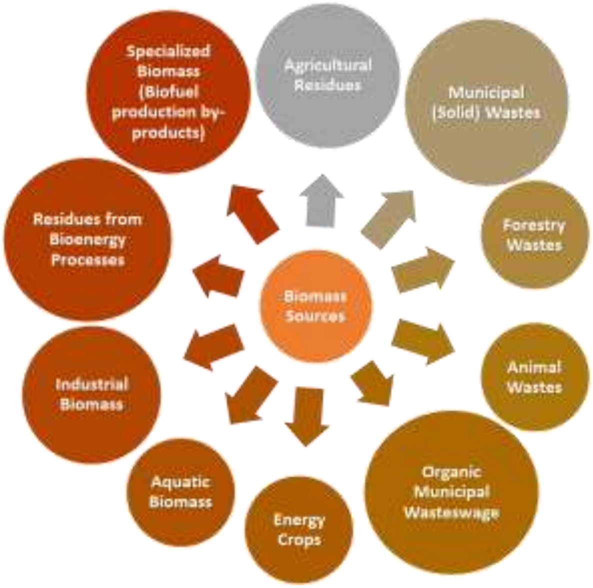

Fig. 2: Categories of biomass wastes based on their origin, composition, and characteristics

Approximately 5 billion tonnes of crop residues are globally generated annually with about 47 %, 29 %, and 7 % produced in Asia, America, and Africa respectively [19], and ~ 2 billion tonnes of municipal solid waste [20]. Waste generation varies from region; and is influenced by socioeconomics, technological advancement, etc. Waste generation is increasing steadily. Without suitable treatment, the waste constitutes environmental challenges and adversely affects human health and well-being and the planet Earth [21]. Many studies have been conducted on biomass utilization for energy production in Nigeria [22]. Rural communities in sub-Saharan Africa (SSA), including Nigeria, face significant challenges related to energy poverty [23]. A substantial portion, approximately 52.3 % of this population, lacks access to electricity. Moreover, over 80 % of these rural households rely on traditional firewood for cooking and utilize non-conventional methods and kerosene for lighting.

1.2 Overview and Motivation

Climate change is redefining and transforming the business-as-usual (BAU) of the global energy consumption and supply system, fostering a paradigm shift and transition from fossil to clean energy like biomass energy and other renewables to become of interest to researchers, Governments of nations and players in energy industries [24]. The availability of abundant biomass energy contributes 14 % to the global energy mix [25] and through the characterization and valorization of more biomass waste materials for bioenergy [26], showing their potential to help in the mitigation by CO_2 trapping and to supply renewable energy [27]. Therefore adequate knowledge of the quality of biomass and its waste is key for bioresources development [28].

1.3 Research Objectives

The research presented in this thesis first assesses biomass residues available in Africa for their bioenergy potential, particularly for modern biofuels (biomethane, bioethanol, etc.). However, alternative and underutilized biomass resources must be identified as feedstocks for bioenergy production or biomaterials for other purposes such as animal feed and feed complements, thereby lowering competition for biomass wastes for diversified uses. This was the second focus of the investigation by which we investigated *Prosopis africana* biomass for prospective bioenergy applications. The aim of this research is to evaluate the potential of utilizing underutilized lignocellulose biomass wastes as biofuel (liquid, solid, and gases). The specific objectives of the research are to:

1 Critically analyze advances and current knowledge on biomass waste valorization for biofuel, pretreatment for biofuel production, and coupling biomass utilization and carbon captures and sequestrations.

2 Evaluate the bioenergy potentials of selected crop residues in Africa using their production, residue-to-product rations, recoverability factor and heating values.

3 Physico-thermo-chemically characterize the biomass wastes using proximate, analysis, ultimate analyses, thermogravimetric analyses (TGA), and scanning electron microscopy (SEM) in view of determining their valorization potential.

4 Valorize biomass wastes for production of densified hybrid solid biofuel (fuel briquette) production, and optimization using response surface methodology (RSM).

5 Conduct socio-economic, barriers, and environmental impact appraisal of the bioenergy solutions.

1.4 Scope and Organization of Thesis

Chapter two brings additional motivation as well as a detailed literature review that serves as the basis for the project, explaining the energy landscape, various routes to valorizing biomass for biofuel, possible barriers and risks hampering the implementations. Chapter three assesses the biomass potential of energy crops in Africa, in the context of energy poverty on the continent. A template for further assessments of underutilized energy crops was developed for further studies. Chapter four considers the characterization of an underutilized biomass waste of *Prosopis africana* for biofuel application by assessing physical, chemical, biochemical, and thermal properties of leaf, bark, pod, and wood biomass wastes of *Prosopis africana* trees. Chapter five shows the application of PA biomass wastes for biofuel production with considerations on particle size, feedstock composition, and densification pressure and binder concentrations that were combined and assessed for their impact on the properties of briquettes, allowing development of new models for briquette production.

CHAPTER TWO

LITERATURE REVIEW

2.1 Nigeria’s Electricity Framework and Landscape

The Federal Government of Nigeria (FGN), supported by the 36 state governments, the Federal Capital Territory (FCT), and the associated offices such as the Presidential Task Force on Power, play a pivotal role in overseeing the country’s energy sector. This involves collaboration involves coordination with ministries, departments, commissions, programs, and other stakeholders (**Fig. 3**) since diverse responsibilities within the country's energy sector are handled by numerous Ministries, Departments, and Agencies (MDAs), including but not limited to the Federal Ministries of Power (FMP), Water Resources, Petroleum, Environment, Science, and Technology. This comprehensive approach ensures effective governance and management of Nigeria's energy landscape with well-connected institutions (**Fig. 3**). There are currently 11 distribution companies, 6 generating companies, and 1 transmission company. They are regulated by the Nigerian Electricity Regulatory Commission (NERC) [29]. The Rural Electrification Policy (REP), introduced in 2005 and officially launched in 2009, delineates the federal government's goals, objectives, and policies about rural areas. This policy establishes guidelines and rights for energy actors, defining rules that govern the rural energy market, and advocates collaboration between government agencies, such as the Nigerian Electricity Regulatory Commission (NERC) and the Rural Electrification Agency (REA), for effective policy implementation. The REP also outlines respective responsibilities and procedures for providing subsidies, emphasizing their role in promoting solar mini- and off-grid systems to expand energy access rather than consumption [30]. The Energy Commission of Nigeria advises the government, while the Government and the FMP set and implement the policies.

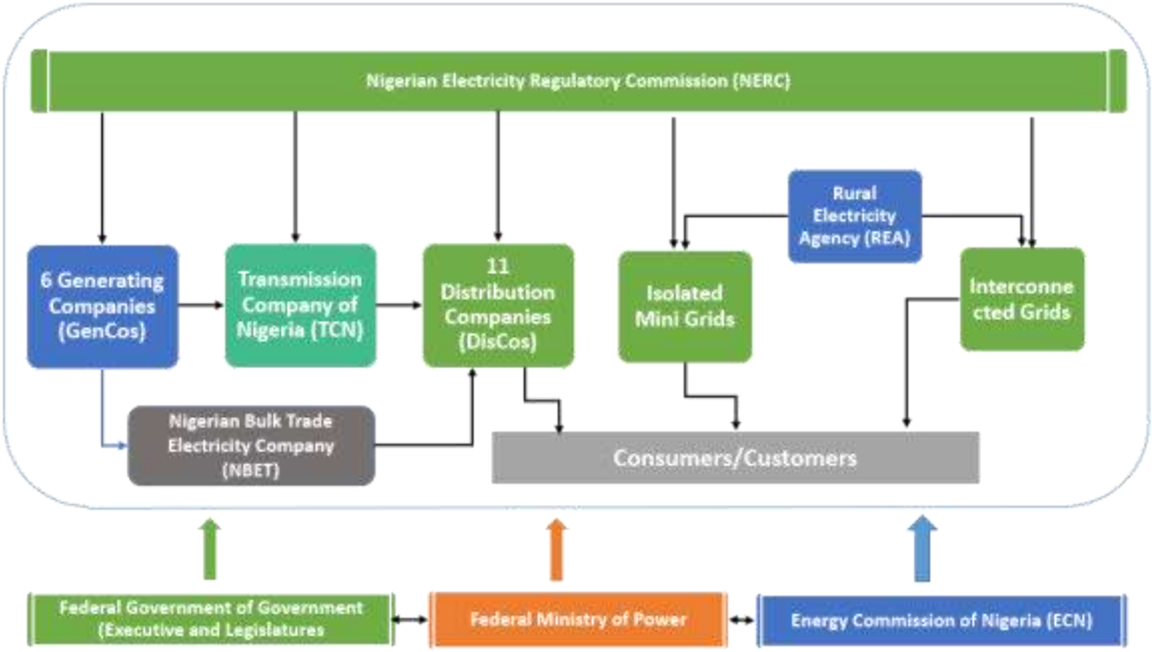

Fig. 3: Institutional Framework for Electricity in Nigeria

Nigeria's Biomass (Bioenergy) Policies, as stated in Nigeria's Energy Master Plan (NEMP), aim to efficiently harness non-fuel wood biomass energy resources and integrate them with other energy sources, promote efficient biomass conversion technologies is a key objective, measure to support initiatives reducing forest thinning and enhancing the collection and utilization of forest residue will be improved, set limits on biomass usage for energy, ensuring accommodation alongside other land demands such as food production and biodiversity conservation, develop a comprehensive life cycle analysis of all biomass feedstock will be undertaken to determine their relative climate change benefits, comprehensively map out agro ecological suitable energy crops and, provide a regional perspective on production potentials to inform decision-making for handling and processing facilities [26].

Federal Ministry of Power (FMP), through its guiding policies under the National Electric Power Policy (NEPP) of 2001, the Electric Power Sector Reform (EPSR) Act of 2005, the Roadmap for Power Sector Reform of August 2010, and finally the Nigerian Electricity Act of 2023 have the responsibility of policy-making for power provision [31]. They do this in affiliation with the Rural Electrification

Agency (REA), Electricity Management Services Limited (EMSL), National Power Training Institute of Nigeria (NAPTIN), and oversight from the National Electricity Regulatory Commission (NERC) [32]. Since 2001, various reforms (**Table 1**) have been proposed to address limiting issues such as poor infrastructure and investment, insufficient generation capacity, and limited access to electricity in rural areas. They have also sought to encourage private sector participation, renewable energy deployment, and enhance regulatory oversight. The Energy Commission of Nigeria (ECN) has a multifaceted and statutory mandate encompassing the field of Energy in all its ramifications and plays a significant role in shaping the energy landscape of Nigeria. The government extended its responsibilities to include developing standards for electrical equipment and devices to mitigate these incidents [33]. It plays a significant role in shaping the energy landscape of Nigeria. As the apex energy agency in the country, ECN is responsible for coordinating and supervising all activities in the energy sector, driving policy formulation, research, capacity building, regulation, and international cooperation to advance the country's energy development goals [34].

Table 1: Electricity Reform policies in Nigeria and their strategic intents

S/N	Reform Policies	Year	Strategic Intents
1	National Electric Power Policy (NEPP)	2001	To liberalize the electricity sector, attract private investment, and improve efficiency and reliability in power generation, transmission, and distribution [35].
2	National Energy Policy (NEP)	2003	To ensure the sustainable development and utilization of Nigeria’s energy resources, including electricity, to meet its national development goals [34].
3	Electric Power Sector Reform Act (EPSRA)	2005	To establish a legal framework for restructuring the Nigerian electricity industry; promote competition, and create a conducive environment for private sector participation [36].
4	Rural Electrification Strategy and	2005	To extend electricity access to rural areas through off-grid and mini-grid solutions, improve livelihoods, and reduce

	Implementation Plan (RESIP)		poverty [37].
5	National Integrated Power Project (NIPP)	2005	To fast-track the development of new electricity generation capacity, construct gas-fired power plants across the country, increase the overall power supply, and reduce reliance on hydroelectricity[38].
6	Nigerian Electricity Regulatory Commission (NERC) Establishment Act	2005	To create an independent regulatory body responsible for setting tariffs, ensuring fair competition, and promoting investor confidence in the electricity sector [39].
7	Power Sector Reform Roadmap	2010	To outline the government's strategy for privatization of the power sector, including the unbundling and sale of state-owned generation and distribution assets to private investors [40].
8	Nigerian Electricity Supply Industry (NESI) Roadmap	2013	To address the challenges in the electricity sector, improve service delivery, and achieve universal access to electricity by 2020 [40].
9	National Renewable Energy and Energy Efficiency Policy (NEP)	2015	To promote the development of renewable energy sources such as solar, wind, and biomass, as well as energy efficiency measures, to diversify the energy mix, increase access to electricity, and reduce greenhouse gas emissions [41].
10	Nigerian Electricity Market Stabilization Facility (NEMSF)	2015	To address financial challenges in the electricity sector and stabilize operations by providing financial support to market participants, addressing revenue shortfalls, and improving liquidity in the Sector [42].
11	Power Sector Recovery Program (PSRP)	2017	To address the challenges facing the power sector, including inadequate generation capacity, poor transmission infrastructure, and financial viability issues among distribution companies, through targeted reforms and investments [43].
12	Nigerian Electricity	2017	To facilitate the development of off-grid and mini-grid

	Regulatory Commission (NERC) Mini-Grid Regulation		electricity systems to increase access to electricity in rural and underserved areas [44].
13	Rural Electrification Strategy and Implementation Plan (RESIP)	2018	To accelerate rural electrification, and underserved areas through off-grid deployment, mini-grid solutions, leveraging renewable energy sources, and fostering public-private partnerships [45].
14	National Mass Metering Program (NMMP)	2020	To address the issue of estimated billing, improve metering in the electricity sector, deploy prepaid meters to customers across distribution companies, reduce losses, enhance revenue collection, and improve customer satisfaction [46].
15	Nigerian Electricity Act	2023	Aims to address persistent challenges in the electricity sector, such as inadequate generation capacity, transmission and distribution losses, tariff affordability, regulatory oversight, etc. [31], [47].

The Rural Electrification Strategy, in conjunction with the Rural Electrification Policy, constitutes the framework to facilitate the extension of electricity services to rural areas. The objective of the Federal Government of Nigeria was to enhance electricity accessibility, aiming for 75 % and 90 % coverage by 2020 and 2030, respectively (**Table 2**). The focus is on integrating renewable energy sources to constitute at least 10 % of the energy mix by 2025, as outlined in the National Electric Power Policy (NEPP) of 2001 and the Rural Electrification Policy of 2005. To meet the 75 % national target, urban electrification needs to achieve 95% coverage, while rural electrification must reach 60 % by 2020. This necessitates connecting over 10 million additional rural households, based on an average of seven (7) persons per household [48].

Table 2: Goals of the Federal Government of Nigeria regarding electricity access and renewable energy contribution

Goal	**Target Year**	**Target Achievement**
Increase access to electricity	2020	75%
Increase access to electricity	2030	90%
Renewable energy contribution	2025	≥ 10%
Urban electrification	2020	95%
Rural electrification	2020	60%
Additional rural households connected	2020	> 10,000,000

Ref: [49], [50]

The FMP through its Renewable and Rural Power Access department has achieved 650 electrical installations, inspections, and testing of various generation, transmission, and distribution power projects. Among these, 450 installations were certified fit for use. NERC, as an autonomous regulatory agency, plays a crucial role in overseeing the electric power industry within Nigeria. Its primary functions include enforcing compliance with market regulations and operational guidelines. Additionally, NERC is dedicated to safeguarding consumer interests by establishing customer service standards, implementing fair pricing rules, and offering effective dispute resolution mechanisms. The commission is also responsible for tariff regulation through the Multi-Year Tariff Order, promoting fair pricing, encouraging competition, and facilitating private sector participation [51].

Generally, the status of electricity access in Nigeria has been poor. The World Energy Outlook 2020 database by the International Energy Agency (IEA) revealed that as of 2019, electricity access in Nigeria stood at 61.6 %, leaving ~ 77 million people without power [52]. Nevertheless, looking at the key metrics (**Table 3**) for the power sector in Nigeria, regarding total customer numbers, metered customers, estimated customers, revenue collected by DISCOs, and electricity supply in Q1 2023 show a positive percentage change compared to the previous quarter and the year-on-year percentage change.

Table 3: Nigeria's Electricity Report adopted from Nigerian Bureau Statistics Q1 2023 Report

Metric	Q1 2023	Q4 2022	Change (%)	Year-on-Year (%)
Total Customer Numbers	11.27 million	11.06 million	1.89	5.99
Metered Customers	5.31 million	5.13 million	3.61	10.86
Estimated Customers	5.96 million	5.93 million	0.40	1.99
Revenue Collected (Naira)	247.33 billion	232.32 billion	6.46	20.81
Electricity Supply (GWh)	5,852	5,611	4.29	-1.74

Ref: [53]

Furthermore, the NERC is saddled with the approval of operating codes, standards regulation, licensing, and regulation of entities involved in generation (> 1 MW), transmission, distribution, and trading. Its mandates extend to monitoring electricity market activities and overseeing market amendments [54], [55]. The Energy Commission of Nigeria is tasked with strategic planning and coordination of national energy policies. Operating under the ECN Act, it advises the federal or state government on funding allocations for the energy sector, covering research and development, production, and distribution. The ECN actively monitors the energy sector's performance in line with government energy policies and serves as a central hub for gathering and disseminating information related to national energy policy [56]. The Federal Ministry of Power is entrusted with initiating, formulating, coordinating, and implementing comprehensive policies and programs to foster electricity generation from diverse energy sources in Nigeria. The ministry is expected to guide other ministries, agencies, and departments (MDAs) that play in the country's power sector [32], [30].

The NERC Guidelines on Distribution Franchising in the Nigerian Electricity Supply Industry 2020 empower Distribution Companies (DisCos) to adapt to evolving business structures and technology. This adaptation is crucial for providing secure and reliable services to end-user consumers. The

Franchising Guidelines enable DisCos to engage in franchising arrangements with third parties, allowing them to perform specific functions within the DisCo's licensed area. The rise of Distributed Energy Resources (DERs) is anticipated to contribute significantly to an integrated grid, fostering efficiency and consumption [57], [58]. This is attributed to the ability of DERs to operate independently from local distribution licenses. Support for mini-grid development has increased recently, enhancing commercial viability and recognizing co-benefits such as national economic development. The evolving mix of DERs facilitates a two-way energy flow, accommodating new connected technologies for power generation. The completion of the Nigeria Electrification Roadmap (NER) is expected to alleviate challenges in power supply, positively impacting industrial, agricultural, and mining sectors by increasing operational capacity to 25 GW [57], [58]. Privatization efforts concerning the National Integrated Power Projects (NIPP), and selected Government Mid/Downstream Energy Assets aim to address transmission and transportation issues, contingent on connected customers paying for consumed power promptly to ensure the flourishing of the generation sector.

The current electricity generation in Nigeria falls short of meeting the demands of households and businesses, leading to a low per capita electricity consumption. The Federal Government of Nigeria (FGN) has established ambitious goals in the National Electric Power Policy and the Rural Electrification Policy. At an electricity installed capacity of 13.5 GW, generation has fluctuated between 3MW and 5 MW [59]. Over the years, many power plants operated below their optimal capacity, resulting in a significant loss of electricity during transmission. For instance, although the electricity capacity was 5600 MW in 2001, actual power generation plummeted to as low as ~ 1750 MW [60]. Therefore, these shortfalls can be closed by introducing and scaling up bioenergy into the energy mix, especially for off-grid systems in rural areas. By 2030, biomass energy contribution (**Table 4**) is expected to hit 800 MW compared to 2015 records. The entire renewable energy capacity is expected to contribute ~36 % of the total energy [61]. However, with more investments, research, and developments in biomass valorization for energy, the capacity and contribution of biomass energy will advance and address the issue of 80 % and 28 % of Nigerians that will not have access to electricity and clean cooking by 2030 respectively [62].

Table 4: Nigeria's Electricity Generation from Renewable Energy Sources

Resources	2010 (MW)	Total Contributions (%)	2015 (MW)	Contributions (%)	2030 (MW)	Total Contributions (%)
Large hydro	1,930	94.79	5,930	19.77	48,000	25
Small hydro	100	4.91	734	2.45	19,000	9.90
Solar PV	5	0.25	120	0.40	500	0.26
Solar Thermal	0	0	1	0.003	5	0.003
Wind	1	0.05	20	0.07	40	0.02
Biomass	0	0	100	0.33	800	0.42
Total Renewable Energy	**2,036**		**6,905**	**23.02**	**68,345**	**35.60**
Total Energy	**16,000**		**30,000**		**192,000**	
Renewable Energy Percentage		**12.73**		**23.02**		**35.60**

Ref: [61], [63]

Nigeria has taken several initiatives in the past towards rural electrification. One primary approach was establishing the Rural Electrification Agency (REA) in 2006 to facilitate the electrification of rural and underserved communities in the country. The REA implements various programs and projects to provide access to electricity in rural areas through grid extension, mini-grid systems, and standalone solar solutions. Progress has been made in increasing electrification rates in rural areas through these initiatives (**Fig. 4a**). The government has collaborated with development partners and private sector stakeholders to mobilize funding and technical expertise for rural electrification projects. However, Bioenergy is not reflected in the energy mix, and despite these efforts, significant gaps still exist in rural electrification schemes with many remote communities existing without access to reliable electricity, thereby hindering socio-economic development and quality of life in those communities. A further result of this misnomer is the continual urban migration and anti-social behavior of middle-aged and able-bodied youths. Challenges such as inadequate funding, technical capacity limitations, and policy inconsistencies continue to impede rural electrification. **Fig. 4a** shows electrified communities with high density in southern Nigeria, while **Fig. 4b** shows power distribution infrastructures with low footprints in the northeastern part of Nigeria. There is a need to improve the existing mini grids (**Fig. 4c**) to reach the wider communities to address the chronic energy poverty in Nigeria. **Fig. 4e** shows the transmission lines, most of which are obsolete and often lead to the collapse of the grid system. There is a need for more independent power plants (**Fig. 4d**) geographically spread to reduce the load on the existing aged transmission substation (**Fig. 4f**)

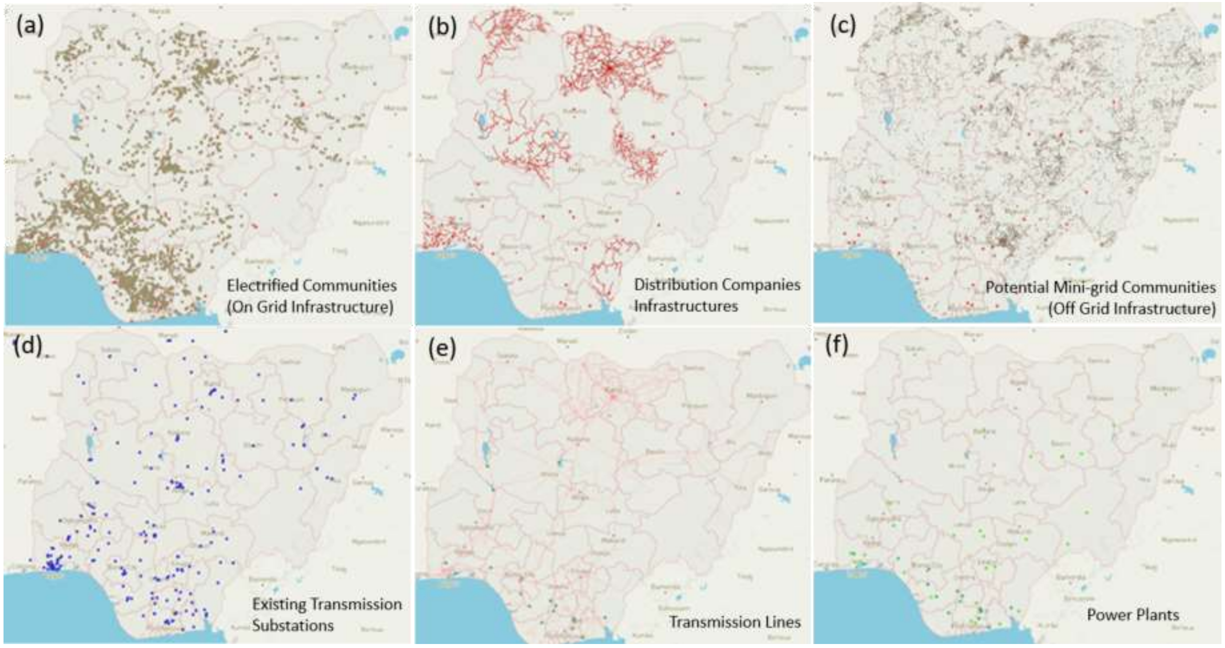

Fig. 4: Nigeria's electricity coverage showing (a) Electrified Communities (On Grid Infrastructure), (b) Distribution Companies Infrastructures, (c) Potential Mini grid Communities (Off Grid Infrastructure), (d) Existing Transmission Substations, (e) Transmission Lines, and (f) Power Plants [64]

2.2 Energy from Biomass

2.2.1 Biomass Resources and Classification

Biomass resources can be of plant or animal origin. They are renewable materials because they can be grown and re-grown. They include agricultural residues, forest residues, energy crops and animal waste as seen in **Fig. 5**. These biomass materials are sustainable energy resources with significant potential for addressing global energy needs while mitigating environmental challenges and promoting rural development. By understanding their diversity based on origin, composition, and application, stakeholders can identify optimal biomass valorization pathways and contribute to a more sustainable energy future.

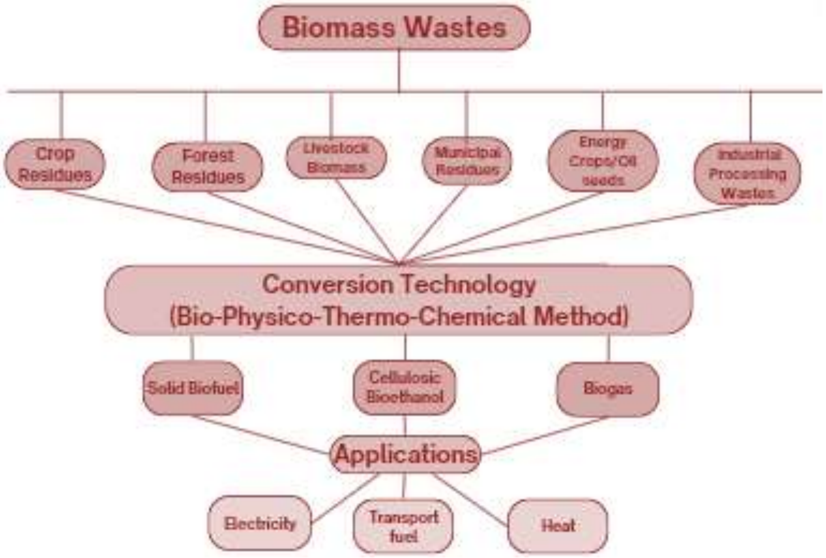

Fig. 5: Biomass Classifications and Conversion Technologies to Bioenergy

2.2.2 Biomass Valorization to Energy in Nigeria

Inconsistent policies, technology limitations, and poor waste management form part of the issues hindering the adoption of biofuels in Nigeria. The Nigeria biofuel policy and incentives released in 2007 were reviewed [65], the recommendation being that the policy should be upgraded as it classified biofuel as only including bioethanol and biodiesel and primary food sources as the main feedstock, neglecting second-generation feedstocks. Therefore, Nigeria needs to review its programs and policies [66]. Nigeria has explored adopting 100 % renewable energy supply by 2050 [67]. The country has experienced setbacks in renewable energy usage due to poorly utilized renewable resources and improper adoption of relevant policies. Efficient and effective policy formulation is critical, and with no global agreement, each nation's political decisions are essential in crafting an effective policy [66]. The urban population in Nigeria currently generates 20.5 million tons of municipal solid waste (MSW), which includes more than 50 % of organics highly suitable for energy valorization [68]. Climate change and environmental issues are issues that are pushing many countries to adopt biofuels. By 2030, the Nigerian Renewable Energy and Energy Efficiency Policy aspires to add 23,000 MW of renewable energy capacity, with agricultural and municipal solid waste being the primary bioenergy sources [68].

Various authors have outlined (**Table 5**) the potential of biomass valorization by assessing the agricultural residues and municipal solid and liquid waste available for producing biofuels, cellulosic ethanol biogas, and other industrial applications [6]. According to a study [69], the bioenergy potential of Nigeria's forest residue is estimated to generate ~ 101 TWh of electricity and bioenergy which can reduce the pump price of petroleum products.

From these studies, it can be concluded that the biomass and agro-waste resources of Nigeria have the potential to contribute significantly towards the energy and electricity mix of Nigeria. However, these potentials can only be translated to reality if the policy and institutional framework, technological skills, and socio-economic landscape are right.

Table 5: Various assessments on biomass valorization for energy in Nigeria

Topic	Objective/Purpose	Methodology	Findings	Conclusion/Implications	Ref
Biomass Valorization to Bioenergy: Assessment of Biomass Residues' Availability and Bioenergy Potential in Nigeria	To investigate the bioenergy potential of agricultural residues and municipal solid and liquid waste in Nigeria	Applied a computational and analytical approach with mild assumptions using data from 2008 to 2018	It showed higher energy generation from biogas than cellulosic ethanol for the same type of residue.	Biogas has diverse applications, including heat and electric power generation, and holds great potential in addressing Nigeria's electricity crisis.	[70]
Preliminary characterization and valorization of *Ficus benjamina* fruits for biofuel application	To explore the potential of *Ficus benjamina* (FB) fruits, typically considered waste, as a biofuel feedstock.	The study utilized various biochemical methods to characterize the physical, thermal, and chemical properties of pulverized *Ficus benjamina fruits* (PFB).	The moisture, ash, volatile matter, and fixed carbon contents are 9.29 %, 6.26 %, 64.35 %, and 20.10 %, respectively. The higher and lower heating values were determined to be 19.74 MJ/kg and 18.55 MJ/kg, respectively.	The results indicate that PFB possesses properties comparable to other biomass feedstocks, suggesting its potential as a solid biofuel. This valorization of FB fruits could contribute to waste reduction and the development of sustainable biofuel sources.	[71]

Biomass utilization for energy production in Nigeria: A review	To conduct a systematic review to assess the progress and major themes in biomass energy recovery in Nigeria, as well as identify challenges facing its utilization for energy production	A systematic search using Boolean-operator keywords was conducted on SCOPUS and Google Scholar databases.	Major themes driving biomass valorization in Nigeria include climate change, energy diversification, waste management, and policies. Challenges include poor waste management, resource limitations, and inconsistent policies.	Nigeria has significant energy potential from crop residues and municipal solid waste. Efforts should focus on developing agriculture and waste management systems and addressing fuel subsidies to make renewable energy ventures more attractive.	[68]
Bio-Fuel Properties and Elemental Analysis of Bio-Oil Produced from Pyrolysis of *Gmelina Arborea*	To determine affordable processes for producing sustainable energy using waste materials	Pyrolysis conducted in a fixed bed pilot-scale reactor using *Gmelina arborea* biomass	Physicochemical properties and ultimate analysis of bio-oil determined	*Gmelina arborea* sawdust biomass shows favorable properties for bio-oil production with low sulfur content	[27]
Valorization of waste cassava peel into biochar: An alternative to electrically powered process	To convert waste cassava peels into biochar using a biomass-powered reactor, addressing the environmental burden caused by increased cassava consumption.	Top-lit updraft reactor with retort heating for the conversion process was used, designed to be cheap, simple, and environmentally friendly.	The study achieved a biochar yield of 55.13 %, with FTIR analysis indicating similar functional groups in the biochar compared to the precursor, but with more	The study demonstrates the feasibility of converting waste cassava peels into biochar using a biomass-powered reactor, offering an environmentally friendly solution for managing cassava peel waste. The biochar	[72]

			oxygenated functional groups.	produced exhibited desirable properties for various applications.	
Valorization of pineapple peel and poultry manure for clean energy generation	To assess energy production from anaerobic co-digestion of pineapple peels (PPs) and poultry manure (PM)	Pretreatment of PPs using sulfuric acid and alkaline hydrogen peroxide (H_2O_2).	Alkaline H_2O_2 pretreatment removed 71.34 % of lignin, reduced hemicellulose by 61%, and increased cellulose content by 39 %.	Alkaline pretreatment of PPs before digestion is recommended for biogas production and quality digestate, useful as biofertilizers or soil enhancers, particularly in regions with significant pineapple production.	[73]
Biomass valorization for energy applications: A preliminary study on millet husk	To investigate the effect of particle sizes, compaction pressures, and binder concentrations on briquette characteristics and assess the economic viability of millet husk briquettes as fuel.	Particle sizes of 0.3, 0.4, 0.6, and 1.7 mm; compaction pressures of 10, 15, 20, and 25 MPa; and binder concentrations (gum Arabic) of 25, 30, 35, and 40 % were used.	Density, impact resistance index, and compressive strength increased with compaction pressures and binder concentrations and decreased with particle size.	Millet husk briquettes show potential as an efficient and cost-effective alternative for domestic cooking, leading to fuel savings, reduced deforestation, and improved profitability of millet cultivation in Northern Nigeria	[74]
Mechanical and Thermomechanical Properties of Clay-	To investigate the feasibility of clay polymer-based	Fabrication of polymeric composites by mixing unsaturated polyester	Morphological analysis shows rough, coarse, inhomogeneous surfaces	Composite combination suitable for roof tile production and applications requiring low	[75]

Cowpea (*Vigna Unguiculata Walp*.) Husks Polyester Bio-Composite for Building Applications	composite with cowpea husk filler for roof tile production	resin with cowpea husk at varying filler weights and curing.	with voids in the mono-reinforced composites, while clay uniformly fills voids in hybrid composites.	strength.	
Physical-Mechanical properties of wood-based composite reinforced with recycled polypropylene and cowpea (*Vigna unguiculata Walp*.) husk	Producing eco-friendly panels from agro and industrial wastes for various applications	Panels produced from cowpea husk (CPH), wood chips (WC), and recycled polypropylene (rPP)	Optimal performance achieved with 80 % WC and 20 % CPH, meeting ANSI A 208.1 standard for physical properties	The CPH, WC, and rPP mixture can be utilized for board production with good dimensional stability, suitable for applications like ceiling boards and wall claddings where load bearing is not crucial.	[76]
Bioenergy Potential of Under-Utilized Solid Waste Residues from Oil Palm Mills in Nigeria	Estimate bioelectricity potentials of under-utilized oil palm processing solid wastes in Nigeria	Employing a quantitative approach to data generation	Bioelectricity potential ranged from 3.234 to 5.175 MWh in 2004, increasing to 3.796 to 6.073 MWh in 2013	Technological, policy/political, and economic challenges identified as hurdles for bioelectricity generation	[77]
The potential of lignocellulosic fiber reinforced polymer composites for	To provide a comprehensive overview of the potential applications and	The paper examines the current state of knowledge, identifies research needs and	The review highlights that lignocellulosic fibers offer several advantages over synthetic counterparts and	Advancements in NFRPCs are crucial to meet the increasing demand for eco-friendly, renewable, and energy-efficient	[78]

automobile parts production: Current knowledge, research needs, and future direction	sustainability of lignocellulosic-based natural fiber-reinforced polymer composites (NFRPCs) in the automobile industry	existing limitations, and provides insights into future perspectives regarding using NFRPCs in the automotive sector.	hold promise as sustainable, high-performance, and cost-effective alternatives. However, continuous research is needed to address issues such as fiber-matrix compatibility, processing techniques, long-term durability concerns, and general property improvement.	materials in automotive design	
Exploring Biogas and Biofertilizer Production from Abattoir Wastes in Nigeria Using a Multi-Criteria Assessment Approach	To assess the potential use of waste generated in the north-central region of Nigerian abattoirs for biogas and biofertilizer production	Data acquired from the study sites were used for computational estimation and integrated into a SWOT analysis to evaluate strengths, weaknesses, opportunities, and threats associated with the prospects of biogas and	The study revealed that high investment costs and public subsidies for fossil fuels are key limiting factors. However, tapping into unexploited carbon markets and multiple socio-economic and environmental benefits favor investment in waste-	Concluded that public support, in the form of national policy reforms leading to intervention programs, is essential for progress in harnessing waste streams from abattoirs for biogas, and biofertilizer production.	[79]

		biofertilizer production	to-energy technologies		
Prospects for biodiesel production from *Macrotermes nigeriensis*: Process optimization and characterization of biodiesel properties	The objective of this study was to produce biodiesel from an insect feedstock (M. *nigeriensis*) and characterize its physicochemical properties, as well as assess its engine performance	Biodiesel was synthesized from M. *nigeriensis* oil using a three-step process involving lipid extraction, acid esterification, and alkaline transesterification. The acid-esterification process was optimized for reaction time, temperature, and methanol-oil molar ratio.	The acid-esterification process resulted in a free fatty acid conversion of 96.58 %. The biodiesel obtained from M. *nigeriensis* oil had a volumetric yield of 86.54 vol.% and contained 96.72 % fatty acid methyl esters (FAME), with a composition of 48 % saturated esters and 52 % monosaturated esters.	The study demonstrated the feasibility of producing biodiesel from M. *nigeriensis* oil and characterized its physicochemical properties. The biodiesel met ASTM standards and exhibited favorable properties for engine performance, including low viscosity and good oxidation stability. These findings highlight the potential of insect-based biodiesel as a sustainable alternative fuel source	[80]

2.2.3 Biomass Energy Production Technologies

Biomass can be converted into valuable energy forms using several different processes and technologies. The factors that influence the choice of the conversion technologies are the type and quantity of biomass feedstock and the desired form of the energy, i.e., end-use requirements, environmental standards, economic conditions, and project-specific factors [81]. Biomass can be converted into three main products: power/heat generation, transportation fuels and chemical feedstock. These conversions to bioenergy are usually carried out using two primary process technologies: thermochemical and biochemical/biological processes [82], depending on waste composition and moisture content as well as product target [83]. Low moisture content and less dense wastes are suitable substrates for thermochemical processes, including incineration/ combustion, pyrolysis, and gasification, while more dense organic waste with high moisture content are suitable substrate for biochemical conversion [83], [84]. **Fig. 6** shows the processes for the valorization of biomass.

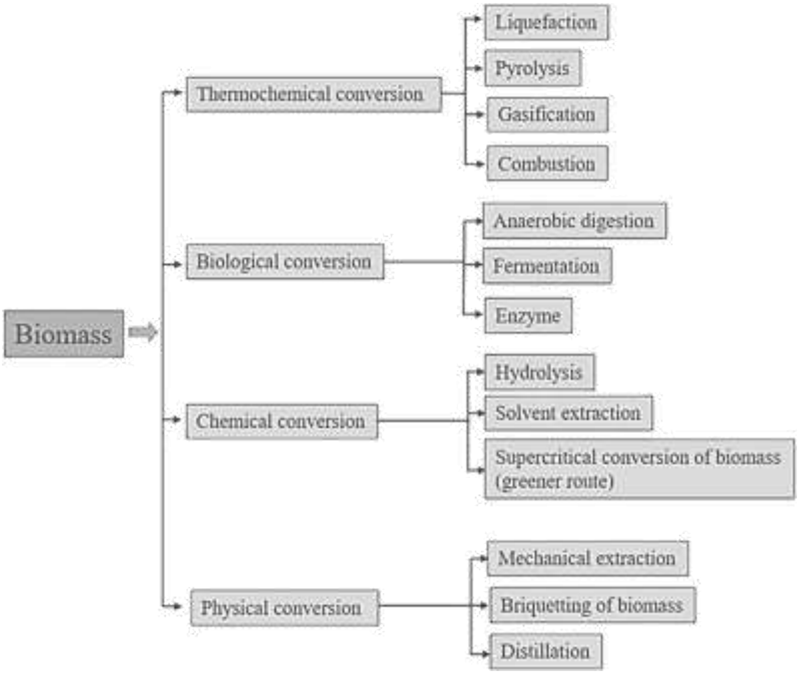

Fig. 6: Various assessments on biomass valorization for energy in Nigeria

In thermochemical conversion processes, the organic wastes undergo high temperatures to produce heat energy, liquid fuel oil, gaseous fuels, and solids like charcoal [83]. The main thermochemical processes include direct combustion, gasification, and pyrolysis [85].

2.2.3.1 Combustion

Combustion is burning biomass in excess air or oxygen in a furnace at temperatures of 800 °C – 1000 °C producing ash and hot gases at high temperatures, which can be used for heating, i.e., in boilers [85]. Combustion reduces the volume of waste by 80 – 90 % and mass by 70 – 80 % [83], thereby reducing the required landfill land space required and increasing the lifespan of existing landfill sites. Combustion also denatures hazardous materials. Hot flue gases generated from combustion heat high-pressure feed water to produce steam which runs boilers, generating electricity [83]. Countries like Denmark and Sweden use this for power production. One major disadvantage of combustion is generating hazardous pollutants that are detrimental to human health and the environment. Direct domestic combustion of biomass is used everywhere in the world, particularly in rural areas in Africa, where firewood is the biomass used in domestic stoves. Co-combustion of biomass in coal-fired power plants has been also explored as it increases the conversion efficiencies of these plants [86].

Co-firing of coal and biomass is currently being used in more than 150 power plants, with the United States, Germany, and Sweden having a higher number of co-firing facilities in the world [87]. Cofiring with biomass reduces GHG emissions by more than 40 % since the combustion of 100 % woody biomass can reduce the emissions by up to 76 % [87]. Cofiring is combines a primary fuel with a secondary fuel for combustion in power plants without alterations to the existing combustion equipment. Co-firing will also be a viable option for Nigeria as it allows for the use of existing infrastructure and reduces capital investment [88]. Roni et al. (2017) [88] provide a thorough review of existing biomass co-firing conditions, policies, challenges, and opportunities around the world. Pulverized combustion is used for co-firing, and it is divided into three categories: direct co-firing, indirect co-firing, and parallel combustion. Direct co-firing comprises feeding fossil fuel together with biomass in the same furnace. Indirect co-firing involves two stages which are the partial oxidation of woody biomass and the syngas combustion to produce hot gases (i.e., heat) [88]. Parallel co-firing entails the installation of an additional boiler for the combustion of biomass to produce steam, which is an expensive combustion option. Co-firing generates electricity with an efficiency between 28 % and 44 % [87]. Industrial combustion technologies entail either a fixed bed, fluidized bed, or pulverized bed technologies. Studies have shown that the theoretical framework for the exergy analysis and advanced exergy analysis of real biomass boilers has been established [89]. Components to be considered for improvement and real fuel-saving potentials were reviewed. The combustion process needs to be highly optimized and an increase in biomass moisture decreases the adiabatic flame temperature, which in turn decreases the total boiler exergy efficiency [90].

Fixed bed boilers are the most used combustion systems due to the low investment cost, energy consumption, and easy assembly. They operate between 850 ℃ and 1400 ℃. In the first stage air primarily goes through a fixed bed where partial combustion, drying, and gasification processes are developed. In the second stage, hot gases produced are completely burned above from a fixed fuel bed where the secondary air is supplied. This stream is greater than the primary air because of the high volatile content in biomass. The char produced provides heat enough to combust the new biomass supplied [87].

Fluidized bed boilers operate as a self-mixing suspension where biomass is mixed with silica sand, limestone, dolomite, or other non-combustible material, which acts as a bed. Biomass is burnt while moving around the combustion chamber while primary air enters from the bottom. Fluidized bed boilers operate between 700 – 1000 ℃ to avoid ash sintering. Fluidized bed boilers are divided into bubbling fluidized beds (BFB) and circulating fluidized bed boilers (CFB) depending on the airspeed. Air demand in fluidized bed boilers is low [87]. Pulverized fuel combustion boilers are like CFB and BFB, but the raw material must have a mean particle size of 20 mm. This technology offers a thermal capacity of 2 – 8 MWth [87].

2.2.3.2 Pyrolysis

Pyrolysis is the thermal decomposition of biomass at temperatures of about 350–600 °C, under pressure, in the total/partial absence of oxygen and it produces three fractions: liquid fraction (bio-oil), solid (chars and ash), and gaseous fractions [91], [87]. Pyrolysis can be conducted under an inert atmosphere or in the presence of hydrogen pressure creating a reductive atmosphere [92]. Pyrolysis can be classified into slow, intermediate and fast pyrolysis considering the residence time of the feed and product vapours inside the reactor and the heating rate. The comparison of the processes is given in **Table 6**.

Table 6: Comparisons of Classes of Pyrolysis

Classification of Pyrolysis	Heating rate °C/s	Products Yield/ %wt.	Advantages	Disadvantages
Slow pyrolysis	≤ 1.5	• Biochar 30-40 • Bio-oil 25-35 • Non-condensable gases 25-35	Upgrade of low-quality feedstocks. Lower emissions of CO, CO_2, NO_x, and dust	long residence time required to obtain the desired product
Intermediate pyrolysis	3-5	• Biochar 25-35 • Bio-oil 40-50 • Non-condensable gases 25	Produces more biochar	Lower tar yield and viscosity in comparison to fast pyrolysis
Fast pyrolysis	10 - 200	• Biochar 12-20 • Bio-oil 60-75 • Non-condensable gases 13-20	The mixture of insoluble organic compounds, i.e. bio-oil produces heat and power in boilers and turbines	High oxygen content in bio-oil compared to fossil fuels

Ref: [93], [94], [95], [96], [97]

Bio-oil is a source of hydrocarbons that can be used for fuel applications after upgrading and is a rich source of functional chemicals such as phenolic compounds, aromatic ethers, furans, etc. Biochar is a solid product obtained by pyrolysis. It can be used for soil amendment/enrichment, as adsorbents, catalysts/catalyst supports, and high-value applications such as supercapacitors, electrodes, etc. Pyrolysis reactor design affects the performance and selectivity of the process [87]

2.2.3.3 Gasification

Gasification is the partial oxidation of biomass to produce a gaseous mixture known as syngas (synthetic gas) which can be further used for power generation or other thermal applications [98]. Syngas is composed of CO, H_2, CH_4, and CO_2 and its composition varies depending on the type of raw material (e.g., coal, pet coke, and biomass) as well as the gasifying agent (i.e., O_2, steam, CO_2, and air) [87]. Carbon-enriched fuels such as coal or MSW are decomposed at high temperatures of 550 – 1600°C in low oxygen required for stoichiometric combustion [83]. Gasification can be classified as auto-thermal and also-thermal, where in auto-thermal gasification, the heat needed to gasify the feedstock is delivered by a part of the input feedstock (i.e., fuel). Gasification compared to combustion processes produces low emissions. There is currently no gasification plant in Nigeria, and it appears that there are only a few cases of application of thermochemical conversion technologies in Nigeria. It is therefore important to study why these technologies are not currently deployed for economic benefit.

2.2.4 Biomass Conversion to Electricity

Nigeria should promote biomass power systems to address the country’s electricity issues and expand the energy mix. The vast agricultural sector and significant biomass resources present a substantial opportunity for biomass conversion to electricity. There are two ways to utilize biomass in electricity production, the first entailing the dedicated use of biomass, while the other involves co-firing biomass with an existing fossil fuel plant. The technologies for biomass conversion in electricity production include direct combustion, gasification, pyrolysis, and biochemical degradation.

According to a study, a Hybrid gas turbine cycle (GTC) and biomass power system (BPS) with an absorption refrigeration system (ARS) for combining cooling, heating, and power (CCHP) can be developed. This reduces CO_2 emissions by ~ 30 % less than standard GTC of the same capacity at a levelized electricity cost of $0.137/kWh [99]. This initiative can address the nation's energy deficits, particularly in rural areas, while promoting sustainable development and reducing greenhouse gas emissions. Direct combustion of biomass in a boiler produces steam, drives a steam turbine connected to an electricity generator. Also, by establishing pilot plants in local government areas, this initiative can serve as a model for rural electrification, enhance local capacities, and contribute to the country's broader energy and environmental goals. Public-Private Partnerships will play a crucial role in funding and implementing these projects, ensuring their success and scalability.

2.3 Barriers to Biomass Conversion to Energy in Nigeria

The country has 785,000 km^2 of accessible farmland [100], [101]. Cultivable land being lavishly available was earlier established by the Food and Agriculture Organization (FAO) [102] in the inventory of forest plantations from different states in Nigeria. The competition between biomass for renewable energy and food is a critical challenge in the country. Since the rise in the price of food in 2007, the competition between the cost of food and biofuel has become a concern [103]. As a result of cases where the biomass used can also serve as food, the use of feed stock that is not edible should be adopted. The impediments to biofuel production in Nigeria are multifaceted and include the high cost of production, weak government policies, limited public awareness, land tenure complexities, and inadequate technological advancements. The cost of processing biofuels currently surpasses that of fossil fuels, rendering the venture unattractive to potential investors [104], [105]. Access to new technology remains a challenge, but both the government and the private sector can play pivotal roles by offering subsidies and interventions.

Weak government policies and a lack of public awareness serve as additional barriers to widespread biofuel adoption in Nigeria. Establishing standardized policies to promote biofuels would be a positive stride, creating a collaborative platform for industries, non-governmental agencies, private investors, research institutes, and academia [106]. Poorly developed biomass utilization policies hamper progress towards its development. Challenges like shortages of policy formulation, and manpower, lack of synergy among policy-making organizations, inconsistency in government vision and programs, absence of enabling legislation, insufficient data on energy potentials, and financial constraints have over the years stunted the progress [22]. Poor institutional framework, inadequate policy implementation [107], lack of coordination, high initial capital costs, weak technology dissemination, insufficient skilled manpower, poor baseline information, and the need for strengthened infrastructure support for increased renewable energy utilization [108].

The prevailing communal control over land in Nigeria, dictated by the land tenure system, introduces barriers for investors, with tribal and inter-ethnic conflicts over land disputes hindering the effective utilization of fallow land in rural communities. Nomadic herdsmen invading arable farmlands further exacerbate the situation, posing a significant threat to farming in various rural areas, resulting in the loss of human lives. Evaluation of biomass conversion facilities should consider treated acres, demonstrated capacity, and multi-stakeholder commitment. To maximize economic benefits, biomass facilities should share economic activity benefits with local communities, encouraging high-return community-based approaches. Co-locating value-added enterprises with biomass facilities enhances economic value and reduces local resource demand [100].

Poor technological advancement is also a challenge, despite satisfying results from the preliminary tests on biomass sources like sugarcane, cassava, coconut, oil palm, and soya. The agricultural practices in the country presents a serious impediment. Notably, the Jatropha Growers, processors, and Exporters Association of Nigeria emphasized the country's need for 2.4 million liters of biodiesel daily to meet the Paris Agreement on climate change [109]. This presents a substantial opportunity for the government and investors to explore. Technology selection should prioritize efficiency, waste capture and reuse, economic self-sustainability, and local investment to build capacity and assets. Careful consideration is needed to avoid outdated and inefficient biomass technology systems.

Logistical expenses associated with collecting feedstock have the potential to diminish economic feasibility. This is primarily due to the economic viability of the project hinging on the availability of biomass feedstock in substantial quantities within a reasonable proximity [110]. Moreover, there is a likelihood that other high-value, non-energy applications of biomass may present competition for bioenergy production.

Investors typically favor shorter payback periods of 2-4 years, a preference that aligns with power plants featuring lower capital costs despite higher fuel expenses. Given the comparatively elevated capital costs of large bioenergy heat and power plants in contrast to gas or coal plants, the attractiveness of bioenergy project investments is contingent on the assurance of long-term policy support and considerations of feedstock prices [111]. The absence of such assurances may deter investment in bioenergy projects. Although renewable energy adoption is not yet deeply rooted in the country, the government is poised to launch awareness programs, developing policies, incentives, and a regulatory environment conducive to the thriving of biofuels in Nigeria [108]. Diversifying energy resources by increasing the share of renewables, accompanied by a reduction in nuclear energy, and fossils in the energy mix increased electricity security [109].

The sustainability aspect is increasingly critical in bioenergy projects, encompassing both environmental and social considerations. Environmental issues include concerns about greenhouse gas (GHG) emissions, land degradation, water resource availability, and biodiversity. Social issues encompass aspects like land ownership, employment opportunities, and social equity. Initiatives in biofuels sustainability, led by the government, private entities, and stakeholder groups, are imperative and require establishing sustainability criteria and indicators covering GHG emissions, food security, biodiversity, and impacts on soil and water. Certification schemes and technical guidance should also be implemented to assess and monitor the impact of bioenergy [112].

2.4 Promoting Biomass Energy Production in Nigeria

2.4.1 Prospects of Biofuel in Nigeria

The power supply in Nigeria is less than 50 % of the installed 6000 MW capacity generated [113], [114], It was estimated that Nigeria would operate 60 million electric generators, which depend on fossil fuel, which is valued at USD 0.25 billion [115], [116]. The challenges outlined earlier make the cost of power generation from fossil fuels high hence biofuel might be a viable alternative that also attracts less political and ethnic attention than the case of fossil fuels [117]. Indicators suggest that biofuel will play a major role in the Nigerian renewable energy sector in the not-so-distant future. The country is endowed with unexploited land, which has attracted substantial investment in sugarcane and cassava plantations among others. The production of cassava as a cash crop is well-developed in Nigeria and has established processing techniques for food products and cattle feed. It has high productivity and adapts easily to climate change, tolerates drought conditions, and low soil fertility, and is prone to few pests [118]. Government incentives to grow cassava for interested farmers have resulted in an average national overturn of about 15 tons of an average national cassava per hectare of land [119]. In the last decade, Nigeria has produced over 577.99 MTons of cassava which is sufficient for bioethanol production to kick off in the country. Also, studies have shown the development of new methods for cassava to bioethanol conversion [120]. Its high starch content makes it a good candidate for high-yield biomass for bioethanol production. The required expertise for the enzyme-aided fermentation process can be obtained locally.

Over 400,000 hectares of land that can boost the high yield of sugarcane production are available in rural Nigeria [121], [122]. Nigeria being a major consumer of sugar, has a high capacity to cultivate sugarcane coupled with the incentives coming from the government to encourage the industry [123].

Nigeria has the largest sugarcane refinery in Africa. Also, the bagasse generated after the sugarcane juice is removed is a huge resource for biofuel production investing in bioethanol is an attractive venture in energy production. The Nigerian government has also given tax waivers to investors in the sugarcane industry since production has been low in recent years [124].

Several plant resources that can be employed as biomass for biofuel and several unexploited and underutilized plant seeds in Nigeria have been identified and characterized [125] Oil has been isolated from some of these seeds for biodiesel production [126], [127] while cellulose has been isolated and characterized from some [128]. Most of these are classified as waste and underutilized. Examples are soybean and *Jatropha circus* (jatropha) oils that have a large potential as biodiesel feedstock is huge in Nigeria. Jatropha oil is nonedible unlike soybean oil; hence it stands at an advantage as biomass for biodiesel production. Cellulose has been isolated and characterized from some plants mostly underutilized or wastes [105].

Solving the waste handling and disposal challenge in Nigeria by finding applications for domestic and industrial waste will be a major economic, social, and environmental achievement. Waste can be directed as biomass for biofuel production. The amount of organic waste generated in Nigeria is stupendous, as reported by [129] in 2013, with about 25 million tons of municipal waste are generated annually in Nigeria according to [130] and several tons of animal waste in Nigeria. These organic wastes can be employed as biomass for biofuel production.

Barriers impeding the use of biomass for biofuel production and utilization include apathy to agriculture and farming due to rural-urban migration, poor access to funding for agricultural practices, nomadic herdsmen, land tenure system, high production cost, poor equipment and technology, food insecurity, lack of public awareness, weak governmental policies and competition between food and biomass for biofuel. Bioethanol and biodiesel were identified as the most sustainable sources of biofuel as renewable energy that can be effectively produced and sustained. Cassava, sugarcane, oil seed plants, and biomass wastes are feasible sources highlighted as biomass to produce bioethanol and biodiesel in Nigeria.

2.4.2 Existing Policies and Development Needs

There is a consensus in Nigeria that renewable energy can play a significant role in the overall energy development of the country [100], [131]. This was amplified by the Renewable Energy Master Plan (REMP) of the country developed by the Energy Commission of Nigeria (ECN), in conjunction with the United Nations Development Programme (UNDP) in November 2005. The overall objective of the REMP is the articulation of the national vision, targets, and a road map for addressing key development challenges facing the country through the accelerated development and exploitation of renewable energy. However, it is worth noting that the capital-intensive nature of biomass technology can deter investment. Further, financing a biomass plant construction could be complicated due to the many conversion technologies that are required on the pilot scale [65], [132]. Policies and ways forward are required as a starting point while five major indicators have to be considered for the development of policies: economic, political, environmental, technological and social.

Economic: This indicator comprises the economic assessment of the energy system regarding its efficiency, electricity cost, and investment cost. The efficiency of the system is to be considered as an integral parameter that reflects the performance of the system as a thermodynamic system. The electricity cost sub-indicator should represent the total energy cost and thus will be a measure of the quality of the system. On the other hand, the investment cost should comprise material cost, design, and the cost of constructing the system [132].

Political: This refers to the political will and determination of the government of the day in formulating and implementing policies and programs that will lead to the project conception, implementation, and development of biomass-based power production [132].

Environmental: This is the governing parameter in the evaluation of a given energy system because, among the greenhouse gases, the CO_2 concentration in the flue gases of the power plant is the most important characteristic for the environmental assessment of the energy system [133]. This is because the evaluation of the concentration of the mixture of gases in each biomass energy system is of primary interest for the quality assessment of the biomass energy system.

Technological: While the parameters for research and development (R&D) in renewable technology are not delineated, a comprehensive technological indicator should encompass a key component which is Development Capital, gauged by the level of R&D investment directed towards biomass-based power plant development [134]. Market elements, informed by energy consumption projections over a period extending up to 50 years, should be considered.

Social: This requires that social aspects have to be taken into consideration in the evaluation of power plants with the following sub-indicators: i) New job opportunity which comprises the number of jobs to be opened per unit MW; ii) Area required and health effect on the surrounding population which is based on the NOX concentration in the surrounding power plant [132]. This indicator is currently becoming very urgent.

2.5 Way Forward

In Nigeria, biofuels have been identified as sustainable forms of renewable energy with possible feedstocks such as sugarcane, cassava, oil seed plants, and waste materials. It has also been noted that the feedstocks are predominantly available and accessible with the possibility of maximizing them to drive socio-economic growth [135]. Valorization of waste materials and non-edible underutilized oil seeds will help minimize the controversies associated with food materials as feedstock for biofuel production in Nigeria and beyond. Nigeria should therefore embark on developing its technology to run biofuel production from the currently developed cassava and sugarcane industry. In this regard, it is pertinent to create more awareness of the contributions of biofuel to the energy mix, and at the same time, provide a suitable business environment for local and international investors [135]. The following are identified for consideration on the way forward toward a more sustainable growth of bioenergy from biomass in Nigeria:

Strengthening the Policy Strategies for Biomass Utilization: The National Energy Policy (NEP) and National Energy Master Plan should be reviewed and strengthened. This would involve conducting a thorough evaluation of the available biomass resources within the country, identifying and understanding existing legislative, regulatory, and institutional structures related to biomass utilization, determining suitable technologies for biomass utilization, ensuring compatibility with local conditions, actively engaging and mobilizing relevant stakeholders to foster collaboration and shared responsibility, implementing initiatives for the development of expertise and skills necessary for effective biomass utilization, evaluating the existing capacities, both institutional and technical, required for successful biomass utilization, conducting awareness programs to educate and inform stakeholders about the benefits and processes of biomass utilization, establishing clear and achievable national targets for biomass utilization, accompanied by realistic timeframes, fostering collaboration at regional and international levels to leverage expertise, resources, and best practices, and ensuring alignment and harmonization of biomass utilization policies with other sectorial policies and global processes [136], [137].

Assessment of the biomass resource available in the country: This involves assessing the biomass resource base which includes the natural resource management structure, planted forests, forest residues, agro-energy crops, agricultural residues, any other biodegradable wastes, municipal solid and liquid wastes in the country and their potentials. It will include the assessment of current trends in the consumption and penetration of conversion technologies for biomass resources in the country [137].

Identifying existing legislative, regulatory, and institutional frameworks: The purpose of this program component is to help in scaling up the sustainable use of biomass as a key component of energy strategies. It involves considering policy decisions or existing laws in the country if there are any in existence to avoid conflict and/or duplication in the process of designing the biomass policy. In this regard, it is important to note that existing regulations are meant to reduce fossil fuel dependence and promote growth and the livelihood of rural populations without affecting food security. Other regulations to be considered would include specific biofuel blending especially those that relate to the production, use, and promotion of biomass as part of the strategies for designing the policy [138].

Identification and Development of appropriate technologies: The conversion technologies should be identified for efficient biomass resource utilization because the achievement of biomass development policy requires careful selection of technologies, coupled with the need to develop the available resources and capacities (technical and human). Among the technologies are improved woodstoves, gasification (biomass combustion for heat and power); bio-digesters, and pyrolysis of wastes, among others [139] [140].

Mobilization and involvement of stakeholders: This helps in designing a biomass policy that will reflect and address the nation’s priorities thus requiring to follow a multi-stakeholder approach to help identify and address the risks, including different interests and concerns to achieve the benefits anticipated. The key factor that impacts on the stakeholder's effectiveness is how it will be carried out (the process to be followed, and the people involved). Some of the key stakeholders would include: i) energy-related central government authorities (ministries, departments, and agencies –MDAs); ii) representatives of states and local governments, non-governmental organizations (NGOs); iii) labor organizations, trade organizations, not forgetting the farmer's organizations and community-based organizations; iv) private sector (Producers, distributors and users of biomass; v) providers of bio-energy facilities; vi) producers of bio-energy technologies, Research agencies, Providers of advisory services and private utilities; and vii) financial institutions (Banks and finance institutions) not forgetting bilateral and multilateral organizations.

Capacity development: These ensure that the relevant know-how is in place because in most cases the level of skills and training determine the level of performance to be achieved. This component is aimed at public, private, and NGOs since it focuses on individuals, institutions, and systems with a long-term commitment. Some of the activities recommended by The United Nations Economic Commission for Africa (UNECA) include: i) strengthening enterprises to source, integrate, install, operate, maintain, and service bioenergy systems; including the provision of business training and incubation support; ii) training policymakers on policies and programs for the acceleration and adoption of bioenergy by small landholders; iii) training the financial and banking sectors (senior management/loan officers) on the risks and rewards of financing biomass-based projects, through pilot projects and programs that minimize initial investment risks [138]. This process ensures that the right people, who possess the required skills, are in place to drive the entire process.

Assessment and identification of institutional and technical capacities: Although many government agencies have been working on various areas of biomass development, only the Energy Commission of Nigeria is entrusted with the responsibility to produce the policy on energy with all its ramifications, although it is expected to involve other stakeholders who have the technical capacities [137]. However, to design a good policy it is important that the country also looks beyond its borders to benefit from lessons learned from other countries within and outside its region.

Sensitization and Awareness Creation of Stakeholders: Although the utilization of traditional biomass by the rural and poor urban settlements has contributed a high percentage of the total primary energy in the country, the potential for modern biomass energy is not known to a great percentage of the population. This is because of the poor awareness and sensitization of the modern technologies available in the country, inclusive of foreign markets, while agro-processing residues and urban wastes are burned in open fields to avoid disposal costs. In this regard, some of the tools that can be used to attract attention and raise awareness and eventual interest of the actors (producers, users, investors, financial and political actors) in agro-processing residues and urban wastes as sources of energy may include national consultation process, workshops, and discussions, dissemination of relevant publications, media campaign [137].

The setting of National Targets with Timeframes: Targets for biomass development based on needs, possibilities, and available implementation capacities and incentives will need to be set in short, medium, and long terms in line with the national priorities and visions [137].

Involvement of regional and international cooperation: Since biomass production, trade and use transcend national borders, policies to be set may become ineffective when they are not broadly supported at regional levels. In this regard, biomass energy sector modernization and rationalization cannot be successfully implemented in Nigeria alone without taking into cognizance the best practices from the neighboring countries. Therefore, it is important to note that policy coherence and long-term effects are best realized under regional contexts [137].

Harmonization with other sectorial policies and global processes: Biomass policy should be an integral part of an overall national energy policy and thus should not be standalone. This implies that it should be an integral part of the agro-industrial development and transport sector strategy, which in turn are part of the national development strategy (macroeconomic and sectorial). In this regard, it is important and necessary to be abreast of the provisions of other sectorial policies relating to energy and biomass in particular when designing biomass policy [137].

Research and Development: It is important to strengthen research and development in Nigeria to be able to develop cutting-edge solutions that will deploy valorized biomass. A lot of underutilized biomass wastes are yet to be identified and characterized by potential biofuel feedstocks, technology development, equipment development, testing facilities, and safety**.**

Mobilizing Investments and Credit Facilities for Adoption of Technologies: Attracting financial resources and facilitating their deployment towards biomass projects is critical. The government should enact policies and regulations that will create an enabling business environment for biomass energy investment. This will increase investors’ confidence. It could be in the form of subsidies, tax breaks, and feed-in tariffs for bioenergy projects. Financing mechanisms tailored to biomass energy projects should be developed such as venture capital, project finance, and public-private partnership (PPP). Development finance institutions, commercial banks, and international donors like the African Development Bank, World Bank, Green Climate Fund (GCF), and Global Environment Facility should be engaged to provide credit facilities and funding for biomass valorization to energy initiatives.

Generally, it can be concluded that there is a need for a comprehensively integrated policy together with a vigorous implementation strategy to facilitate the rapid diffusion of renewable energy in the country’s energy mix. The existing flow of information on renewable energy technologies is inadequate and without the wide establishment of demonstration projects on various energy forms to exhibit the performance and efficiency with which services are delivered. Such projects are likely to sensitize the public and assist in the creation of markets for renewable energy. Further, there is a need for capacity building both at institutional and personnel levels to help in the identification and acquisition of technical, organizational, and managerial skills required for the increased development of renewable energy. In this regard, activities relating to entrepreneurship and managerial skills development training programs and technical courses in renewable energy technologies can be established. These will be used to identify and nurture Energy Service Companies to provide services to rural areas. Lastly, the current Research and Development centers and technology development institutions will need to be adequately strengthened to support the shift towards increased renewable energy utilization [141].

Establishment of Pilot Projects

To further drive the advancement of rural electrification in Nigeria, it is imperative to establish pilot bioenergy plants in each local government area (LGA). These will serve as demonstration and training centers, showcasing the potential of bioenergy to power mini off-grid electricity systems for rural communities. They will further demonstrate the viability of bioenergy, build local capacity, and create a scalable model for broader implementation. Funding can be secured through Public-Private Partnership (PPP) arrangements, leveraging the strengths and resources of both the public and private sectors.

2.6 Conclusions and Missing Gaps

Nigeria has the largest population and the highest number of naturally occurring conventional and renewable energy sources in Africa. Yet, its energy deficit has reached crisis proportions to the extent that ~ 40% of the population has little access to reliable, affordable, and sustainable energy and electricity, leading to enormous economic, social, and political problems. The government has embarked on several energy and electricity policy reforms including liberalization of the sector, removal of subsidies, promotion of renewable energy, and transition from fossil to renewable fuels including biomass. The success of Nigeria's energy landscape transformation and transition from fossil fuels to clean biofuels with net-zero emissions relies immensely on identifying technological gaps, developing and deploying the technologies economically, and prioritizing sustainability in energy policies. This review aimed to provide comprehensive information on existing knowledge on biomass valorization to bioenergy and electricity towards facilitating the successful implementation of government policies, research findings, and private sector interventions in increasing the contribution of biomass to Nigeria’s energy mix. The systematic review approach and meta-data analysis were used to analyze literature from the Google Scholar database and the websites of relevant organizations from 2014 to 2024. Results show that the following feedstock have been evaluated to have potential for biomass conversion into bioenergy and electricity: crop residues; forestry residue; livestock waste; algae and aquatic plants;

energy crops, oil seeds; and domestic and industrial waste. These can be converted to heat, electricity, liquid fuels, biogas, and solid fuels such as briquettes. The various projects that have been executed employed biochemical, thermochemical, and mechanical processes to produce products such as biomethane, biohydrogen, biochar, briquettes, and biodiesel. Technological processes used include fermentation: anaerobic digestion, gasification, pyrolysis, drying, pelletizing, extraction, and separation processes. Although several projects have been implemented, the contribution of biomass to bioenergy and electricity production in Nigeria is still insignificant compared to other sources. The barriers identified include uncertainty with feedstock availability; land availability and conflict with food security; access to technology; poor technological skills; absence of good business models for users; low level of investments in the sector inadequate and poor policy implementation and high initial costs. Recommendations towards promoting biomass conversion to bioenergy and electricity in Nigeria include: developing and implementing policy for biomass utilization; assessment of the biomass resource available in the country; identifying and appraising existing legislative, regulatory, and institutional frameworks; identification, development, and deployment of appropriate technologies; sensitization and mobilization of stakeholders; skills and capacity development; setting and pursuit of national targets with timeframes; regional and international cooperation; harmonization with other sectorial policies and product-driven research and development. If these recommendations are implemented, the contribution of biomass to Nigeria's energy mix can increase by at least 30 %, leading to a significant reduction in the energy deficit in Nigeria.

Missing Gaps

1. While some studies have assessed bioenergy potentials in some countries, there is a lack of extensive meta-analyses that consolidate data across different African countries, thereby limiting the understanding of biomass availability and energy potential on a continental scale.

2. There is no data on the physicochemical properties of the underutilized Prosopis africana to establish their potential for biofuel production.
3. Although initial studies have examined briquette production from biomass, there is a lack of comprehensive optimization studies that consider various factors such as particle size, binder concentration, and densification pressure across different biomass types and properties.
4. Further research is required to evaluate the environmental impacts associated with large-scale biofuel production from agricultural residues. This includes lifecycle assessments that consider GHGs emissions, land use changes, and biodiversity impacts.

There is a need to increase the contribution of biomass and agro-waste to bioenergy and electricity in the energy mix to harness biomass wastes. Not much has been done regarding comprehensive and implementable studies to combine the knowledge available for rural electrification using biomass. There are unwilfully implemented policies and a lack of programs, research, private sector interventions, etc. on the subject. Bioenergy should be considered and deployed by defining a sustainable path toward achieving significant rural electrification using off-grid electricity. Academic institutions like the African University of Science and Technology (AUST) through research and development activities have conducted studies on the potential of biomass for rural electrification in Nigeria. Existing knowledge on biomass-based rural electrification is often fragmented across different sources, making it challenging for stakeholders to access comprehensive and up-to-date information. Furthermore, there is a lack of synthesis and analysis of existing data and experiences, hindering the identification of best practices, lessons learned, and gaps in knowledge. The rest of the thesis reports work done to address each of the missing gaps in knowledge.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Research Design

This research adopts a mixed-methods approach with both quantitative and qualitative analyses. Quantitative methods assessed the biomass properties and energy potential, while qualitative insights addressed socio-economic barriers, scalability and commercialization. To determine the viability of underutilized biomass wastes (specifically Prosopis africana and agricultural residues) for biofuel production, bioenergy potential analysis, optimization, and socio-economic appraisal were incorporated. The overall methodology of the research is shown in **Fig. 7.** Detailed methodoly are explained in chapter four, five and six, where chapter four assesses the biomass potential of energy crops in Africa, in the context of energy poverty on the continent and develops a new method for further assessments of underutilized energy crops was developed for further studies. Chapter five considers the characterization of an underutilized biomass waste of *Prosopis africana* for biofuel application by assessing physical, chemical, biochemical, and thermal properties of leaf, bark, pod, and wood biomass wastes of *Prosopis africana* trees. Chapter six shows the application of PA biomass wastes for biofuel production with considerations on particle size, feedstock composition, and densification pressure and binder concentrations that were combined and assessed for their impact on the properties of briquettes, allowing development of new models for briquette production.

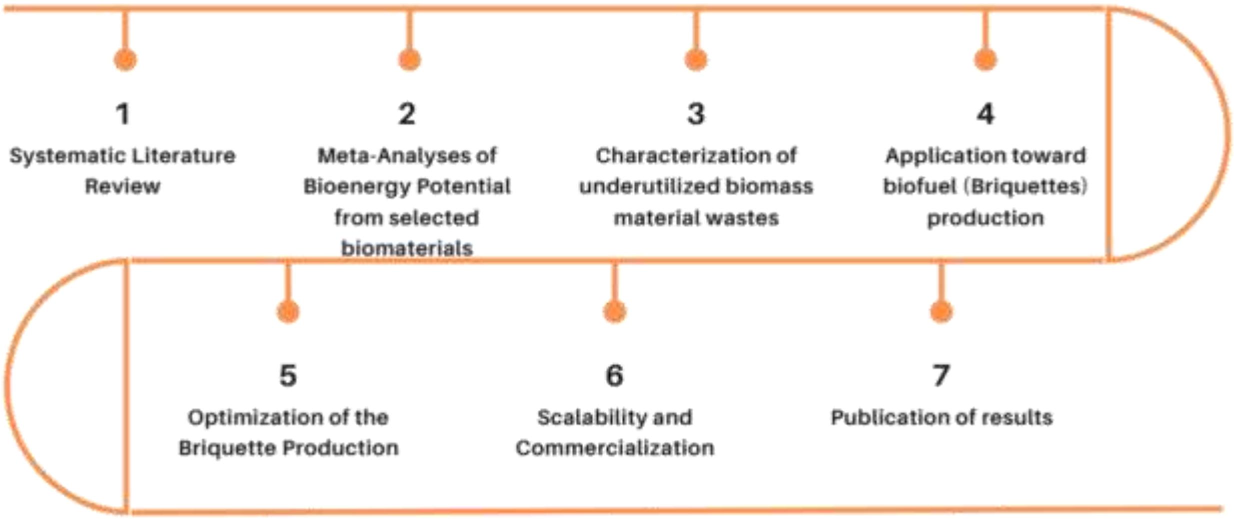

Fig. 7: Research Methodology Framework

3.2 Data Collection Methods

The data were categorized into two; primary and secondary data. The primary data were collected by conducting proximate and ultimate analyses, thermogravimetric analysis, Fourier-transform infrared spectroscopy (FTIR), and scanning electron microscopy (SEM) to analyze physical, thermal, and chemical characteristics of biomass samples.

The secondary data utilized were the datasets from FAOSTAT databases and other relevant energy/agricultural databases to quantify biomass availability, waste production rates, and current energy potentials.

3.3 Materials and Experimental Procedures

- **Sampling**: Collection of biomass residues including agricultural by-products and Prosopis africana samples (pods, bark, wood, leaves).
- **Preparation**: Pulverization and preprocessing of biomass samples for consistency across tests. Ensure particle size variation to assess optimal conditions for briquette production.
- **Analytical Techniques**: Assessment of selected crop residues' energy potential at the continental scale.
- **Proximate Analysis**: Determination of the moisture, ash, volatile matter, and fixed carbon content.
- **Ultimate Analysis**: Determination of the elemental composition (CHNS/O) using CHNS analyzers.
- **Thermogravimetric Analysis (TGA)**: Assessment of the thermal stability and decomposition

temperatures.

- **FTIR and SEM**: Identification of the functional groups and understudying surface morphology.

3.4 Modeling and Statistical Methods

Response Surface Methodology (RSM): This was used to optimize briquette production by examining particle size, binder concentration, feedstock composition, and densification pressure.

ANOVA (Analysis of Variance): This was used to conduct statistical testing to validate findings and assess the influence of variables on energy, mechanical and combustion properties.

3.5 Biofuel Production Process

- **Briquette Fabrication**: The optimized blend of Prosopis africana pod and cowpea husk biomass was used to fabricate hybrid briquettes.
- Evaluation of Briquettes: The energy, physical, mechanical and combustion properties of the briquettes were evaluated, with an interactive model to assess the effect of the independent variables such as particle size, binder concentration, feedstock composition, and densification pressure.

3.6 Data Analysis Techniques

Descriptive Analysis was used to present data on the bioenergy potential of various biomass types and the environmental implications, while the Correlation and Regression Analysis were used to investigate relationships between biomass properties and biofuel efficiency. Scenario Analysis was developed for biomass utilization under different socio-economic and environmental policies.

3.7 Ethical Considerations

Transparency and Data Integrity: Maintained high standards in reporting all results, whether positive or negative, to ensure the methodology's reproducibility and accuracy.

CHAPTER FOUR

BIOENERGY POTENTIAL ASSESSMENT OF BIOMASS RESIDUES IN AFRICA TOWARDS CIRCULAR ECONOMY

4.1 Introduction

Global energy demands have experienced a significant increase due to economic progress, urbanization, and population expansion. According to data from 2009, global energy consumption was 482 exajoules and was increased to 584 exajoules by 2019 [142]. Energy Access is a crucial factor in any nation's socioeconomic development and has presented significant global challenges, impacting all aspects of human existence [143]. Bioenergy development in Africa has presented a growing opportunity for youth employment. In South Africa, the sector created 26,246 jobs in 2016 [144]. A single 800-liter biofuel plant in the country generates approximately 500 jobs. By 2030, the renewable energy sector is projected to create 4.5 million jobs across Africa [144]. This includes opportunities for off-grid renewable energy entrepreneurs, distributors, installers, and technicians. Energy outlooks for Africa tend to favor increased reliance on fossil fuels, disregarding the potential of transitioning from traditional to modern bioenergy sources [145].

The literature [146] suggests that solid biofuels in Ghana have the potential to satisfy more than 50% of the national wood fuel demand. Additionally, biomethane could cover 11.70 % of LPG demand, while bioethanol-based electricity could fulfill approximately 91.2 % of the national electricity demand, suggesting bioethanol's potential to support regional energy needs. Further studies [147] demonstrated the bioenergy capacity in Ghana's renewable power sector in alleviating energy poverty. According to the study, by 2050, ~ 18 TWh of electricity, equivalent to 16.9 % of Ghana's total demand, could be generated from bioenergy for grid balancing. This would also result in a decrease in electricity costs. This indicates the feasibility of a cost-effective, bioenergy-balanced renewable power system for Sub-Saharan Africa. Further studies revealed that the cost of energy generation from biomass gasification and combustion plants ranges from US$ 0.29/kWh to US$0.34/kWh [148], inferring that using crop residues for electricity could be a viable option for rural electrification, provided there is sufficient financial support. In Uganda, crop and animal residues offer an energy potential of 260 PJ annually, highlighting the significant potential of agricultural and forest residues as primary renewable energy sources for Uganda [149]. Converting lignocellulosic farming residues and animal waste into bioenergy is a promising waste management and renewable energy strategy [8]. It holds significant promises for promoting a circular economy in Africa. The increasing demand for renewable energy sources has increased interest in utilizing agricultural residues for bioenergy production [9]. These biofuels can be in liquid, solid, and gaseous forms. Some examples of the liquids are bioethanol, bioethanol, and bio-oil. The gaseous biofuels are biogas, syngas, and biohydrogen, while the solids are biochar, briquettes, and pellets. A study on the valorization of 15 African crops, including banana, barley, cassava, cocoa beans, maize, oats, rapeseed, rice, seed cotton, sugar beet, sugarcane, sunflower seed, sweet potatoes, triticale, and wheat, revealed that the continent could produce 31,303 Mm^3 of bio-methane and 1141 PJ of bioenergy annually. Combining bio-methane in combined heat and power (CHP) systems can generate 109.7 TWh of electricity and 133 TWh of thermal energy annually, potentially supplying 16.3 % of Africa's electricity needs [150].

In Zimbabwe, bio-waste availability for energy generation (agricultural residues, municipal solid waste, animal dung, and sewage sludge) produces 539 PJ annually from 49 Giga tons of bio-waste. Despite being underutilized, these bioenergy sources could potentially fulfill 42.3 % of the country's energy demands, boosting industrial activities in Zimbabwe [142]. Segura-Rodríguez *et al*. [151] examined the potential of sustainable bioenergy in Mali, highlighting that crop residues, livestock waste, and municipal solid wastes (MSW) could reduce dependence on traditional fuels in urban areas where the demand for cooking energy exceeds the biomass availability. It was concluded that briquettes would offer a transitional fuel, biogas, from MSW to assist urban waste management. However, exploring alternative clean energy solutions such as renewable energy and electric cooking systems is imperative to ensure access to clean cooking. To improve access to power, it is necessary to increase the availability of electricity in rural areas by implementing both on-grid and off-grid solutions [152]. Gabisa *et al*. [153], studied bioenergy in eastern Africa. They discovered that Ethiopia has significant untapped biomass residues, which can be utilized sustainably without negatively impacting the socio-economic, the environment, and food security. The country's total bio-energy potential is estimated at 750 PJ per year, derived from forest residue (46.5 %), crop residue (34 %), livestock waste (18.8 %), and municipal solid waste (0.05 %). To maximize these potentials, the study suggested the establishment of an integrated bio-energy database, implementing research and development activities, and identifying feasible bio-energy feedstock value chains. Furthermore, evaluating the bio-energy value chain across its complete life cycle is advisable.

In Tanzania, research has shown that biomass residue production has the potential to generate renewable electricity from off-grid diesel generators using anaerobic digestion (AD) and gasification. In 2018, its biomass streams (agriculture, forestry, livestock, and urban waste) delivered an energy potential of 385 PJ, sufficient to produce 1.2 times the country's electricity output when coupled with diesel generators [154].

There is a need for extensive research and development in biomass valorization of underutilized crop residues in Africa. For example, Tunisia is exploring olive oil, date palm, and almond value chains. Olive oil waste showed the highest bioenergy potential (82%), yet only a tiny fraction is utilized. Date palm fruit and almond hulls also hold significant untapped potential [155]. In the case of Nigeria, bioenergy potential from agricultural residues and municipal waste was assessed, and it was found that the selected biomass had a greater biogas yield than cellulosic ethanol [70]. The agricultural residues have the potential to produce 14,766 ML/year of ethanol and 15,014 Mm^3 per year of biogas. Biogas offers versatile applications, including electricity generation, which can help to address Nigeria's power crisis and support Sustainable Development Goal (SDG) 7. **Table 7** shows the production capacity of the primary biomass produced in Africa from 2010 to 2022.

Table 7: Africa's Production Capacity (Mt – Million tonnes) of the main biomasses (2010 – 2022) [156]

S/N	Biomass	African Producers
1	Bananas	Angola (46.624 Mt), Kenya (19.92 Mt), Egypt (15.92 Mt), Democratic Republic of Congo (10.43 Mt), Sudan (9.80 Mt), Ethiopia (7.59 Mt), Mozambique (6.5 Mt), South Africa (5.17 Mt)
2	Barley	Ethiopia (26.59 MT), Morocco (25.06 Mt), Algeria (16.69 Mt), South Africa (4.37 Mt), Egypt (I.36 Mt)
3	Beans	Kenya (8.798 Mt, Ethiopia (8.25 Mt), Angola (4.2 Mt), Mozambique (3.64 Mt), Democratic Republic of Congo (3.16 Mt)
4	Cassava	Nigeria (717.65 Mt), Democratic Republic Congo (248.65 Mt), Angola (134.59 Mt), Mozambique (66.36 Mt), Ivory Coast (59.29 Mt), Central African Republic (16.50 Mt)
5	Groundnuts	Nigeria (53.92 Mt), Sudan (24.24 Mt), Ghana (7.06 Mt), Democratic Republic Congo (5.89 Mt), Central African Republic (5.52 Mt)
6	Wheat	Egypt (115.56 Mt), Morocco (68.88 Mt), Ethiopia (59.64 Mt), Algeria (38.35), South Africa (23.73 Mt), Kenya (4.14 Mt)
7	Maize (corn)	South Africa (171.61 Mt), Nigeria (136.80 Mt), Ethiopia (111.73 Mt), Egypt (98.02 Mt), Tanzania (76.58 Mt), Malawi (45.04 Mt)
8	Millet	Niger (44.22 Mt), Nigeria (24.88 Mt), Mali (22.22 Mt), Sudan (13.8 Mt), Ethiopia (12.58 Mt), Burkina Faso (12.52 Mt), Senegal 10.19 Mt)
9	Potatoes	Egypt (64.9 Mt), Algeria (57.84 Mt), South Africa (30.96 Mt), Kenya (26.22 Mt), Morocco (23.40 Mt), Tanzania (16.19 Mt), Rwanda (16.19 Mt),
10	Rice	Nigeria (98.86 Mt), Egypt (64.97 Mt), Madagascar (53.46 Mt), Tanzania

		(38.69 Mt), Mali (31.74 Mt), Guinea (27.91 Mt), Ivory Coast (22.98 Mt)
11	Sorghum	Nigeria (85.94 Mt), Ethiopia (58.37 Mt), Sudan (47.31 Mt), Burkina Faso (22.77), Niger (21.30 Mt), Mali (18.5 Mt), Malawi (26.78 Mt),
12	Sugar Cane	South Africa (227.16 Mt), Egypt (204.66 Mt), Kenya (82.11 Mt), Eswatini (72.28 Mt), Uganda (63.4 Mt), Sudan (62.58 Mt), Zambia (57.97 Mt), Zimbabwe (45.02 Mt)
13	Oil Palm	Nigeria (120.62 Mt), Ghana (31.03 Mt), Ivory Coast (27.08 Mt), Democratic Republic Congo (23.52 Mt), Guinea (11.08Mt), Benin (7.7 Mt), Togo (6.41 Mt)
14	Yam	Nigeria (610.39 Mt), Ghana (102.24 Mt), Ivory Coast (86.91 Mt), Benin (39.16 Mt), Togo (10.79 Mt), Cameroun (7.2 Mt), Central African Republic (5.76 Mt)
15	Soya Beans	South Africa (13.79 Mt), Nigeria (10.12 Mt), Zambia (3.52 Mt), Benin (2.17 Mt), Ghana (2.13 Mt), Malawi (2.01 Mt)

The energy crisis significantly impacts developing nations, particularly African states, due to their heavy dependence on non-renewable energy sources and limited capacity to ensure a stable energy supply. However, they possess many untapped renewable energy resources, such as wind, solar, geothermal, biomass, and hydro [157]. Assessment of the present resources is essential to predict their future availability and guarantee a sustainable supply because there is a significant potential to harness energy from crop residues and residual biomass [145]. These crop residues offer a sustainable opportunity for generating off-grid energy in rural areas of Africa through various conversion methods. The current focus is on using agricultural residues such as rice husk, maize stover, and cassava peels as alternatives to firewood and charcoal, providing cleaner energy sources for cooking, industrial heat, and electricity generation in rural areas of Africa without access to electricity [152]. Biomass is more economically viable than other renewable energy sources, requiring less initial investment and having lower production expenses per unit [158]. Valorization of valuable products can be categorized into three approaches for biofuels, as shown in **Table 8** [159].

Table 8: Novel Approaches to Biomass Valorization to Biofuel or Bio-oil

Approach	**Description**
Fractionation and Processing	The biomass is fractionated into its components, typically by removing lignin through pretreatment, making carbohydrates accessible for hydrolysis and fermentation [160], [161], [162]. This process yields bioethanol as the main product. Hydrolysate or fermentation effluents can also be used for biogas or biohydrogen production through anaerobic digestion or photo/dark fermentation [163]. Reductive catalytic fractionation (RCF), a sustainable approach, extracts lignin through solvolysis, depolymerization, and stabilization using redox catalysts. This method yields phenolic units and monolignol, further utilized for various value-added products [164].
Partial Degradation and Upgrading	The biomass undergoes partial degradation, such as pyrolysis, to produce bio-oil, which is further upgraded to improve the fuel properties [165], [166].
Complete Destruction into Syngas	The biomass is completely decomposed into syngas (Carbon monoxide and Hydrogen gas) through gasification, which could serve as a precursor for hydrogen production or can be converted into fuels and organic chemicals via Fischer–Tropsch (F-T) synthesis [167]. Catalytic biomass gasification has gained attention for its potential to improve gasification efficiency [168], [169]. However, challenges such as methane and tar presence in syngas complicate the economic viability of biomass gasification. The produced gas can also be directly combusted for energy generation [170], [171].

Many studies have shown the feasibility of using crop residues for biofuel production in Africa. However, these studies have been for specific countries and there is no published work on a consolidated feasibility for the continent where many of the countries are taken together.

This study aims to evaluate the availability of crop biomass residue resources in African agricultural systems for bioenergy production and to determine if these residues can sustainably generate modern bioenergy. The objective is to quantify the total and recoverable crop residue biomass and assess the bioenergy potentials to produce biofuels (solid, liquid and gaseous) across the continent of Africa. The study considers residues from 30 crops widely cultivated across Africa. Standard procedures are applied, considering global and regional bioenergy sources and local variations. The study addresses data deficiencies in bioenergy resources, including feedstock availability and regional distribution. It establishes a baseline for estimating regional biomass residues and provides a foundation for future research on bioenergy utilization's social, environmental, economic, and technical aspects. The data and recommendations will assist bioenergy practitioners, analysts, academics, and policymakers in formulating policies and strategies.

4.2 Methods

4.2.1 Data Sources and Preparation

The process involves assessing the biomass resource potential of selected agricultural residues excluding livestock wastes, and their bioenergy potential, with emphasis on briquette, biogas, and bioethanol. An in-depth analysis was conducted to examine the socio-technological and economic impact. The biomass residue estimations from the selected energy crops in Africa were based on detailed calculations using data from the public domain. The annual crop production data (**Table 9**) for the study were obtained from the FAOSTAT [156] database from 2010 to 2022. Twenty-five (25) crops were selected based on three criteria: (1) extensive cultivation in African countries, (2) processing and field-based residues, and (3) data availability from these residues.

Table 9: Selected Crop Production in Africa in Million Tonnes (Data source: FAOSTAT [156])

S/N	Crop Residues	No of Countries	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	Total
1	Bananas	45	17.98	18.40	18.22	20.54	19.81	19.78	19.31	19.01	20.43	20.73	21.70	22.64	22.83	261.37
2	Barley	35	16.61	17.38	17.88	19.67	19.43	20.88	18.53	19.80	21.23	20.29	18.02	20.29	5.87	235.88
3	Beans	40	5.27	5.80	6.20	6.49	6.53	7.19	6.93	7.74	7.16	6.85	7.15	8.02	7.83	89.16
4	Cabbages	33	3.04	2.76	3.08	3.10	2.94	3.28	3.19	3.21	3.24	3.50	3.82	4.04	4.37	43.58
5	Cashew nuts	17	1.69	1.69	1.57	1.48	1.46	1.72	1.59	1.86	2.00	1.82	1.95	2.08	2.14	23.05
6	Cassava	42	143.87	151.86	155.84	160.14	163.45	167.12	174.28	178.54	196.94	190.83	194.24	201.45	208.63	2287.18
7	Coconuts	20	2.08	2.13	2.12	2.21	2.20	2.08	2.27	2.25	2.16	2.13	2.08	2.06	1.97	27.74
8	Cotton seed	41	2.07	2.36	2.72	2.58	2.67	2.43	2.55	2.73	2.98	3.02	2.82	2.95	0.00	31.87
9	Groundnuts	46	13.98	12.79	14.01	14.23	15.63	15.43	15.76	16.73	18.72	18.26	19.20	18.28	17.36	210.37
10	Lemons	31	1.05	1.11	1.12	1.15	1.26	1.34	1.33	1.51	1.55	1.58	1.84	1.84	1.98	18.67
11	Lettuce	18	0.35	0.32	0.33	0.35	0.39	0.47	0.45	0.46	0.44	0.51	0.60	0.58	0.60	5.85
12	Maize (corn)	53	69.01	68.75	74.16	73.48	82.07	75.60	75.39	92.38	85.07	85.81	96.01	102.08	94.58	1074.41
13	Millet	40	16.14	10.24	12.30	11.54	12.91	12.65	13.61	12.80	15.77	13.54	15.05	11.62	14.60	172.77
14	Oil palm	22	17.90	17.86	18.66	19.02	19.50	19.76	20.43	21.46	22.13	22.67	23.61	26.50	26.74	276.25
15	Oranges	39	7.49	8.02	8.59	8.92	9.26	9.39	8.86	9.53	9.59	9.96	10.59	10.17	10.75	121.12
16	Pepper	20	3.57	3.59	3.90	3.90	4.14	4.28	4.37	4.33	4.67	4.96	4.91	4.51	4.68	55.79
17	Potatoes	45	24.79	26.52	28.55	29.13	24.07	25.07	22.85	24.04	25.29	26.33	27.68	27.40	27.15	338.88
18	Rice	45	25.96	26.76	29.14	28.94	31.60	32.04	37.21	36.25	36.96	36.43	37.82	38.59	39.88	437.58
19	Sorghum	45	25.07	23.99	23.58	25.29	29.32	26.11	30.24	27.56	29.99	27.96	28.21	26.40	29.57	353.29
20	Soya beans	28	1.60	1.90	2.13	2.20	2.49	2.64	2.82	3.69	3.81	3.61	4.50	5.52	4.54	41.47
21	Sugar cane	43	87.40	89.35	90.91	97.88	95.16	92.58	91.93	92.55	96.42	96.81	96.98	96.23	97.63	1221.84
22	Sweet potatoes	46	16.86	18.04	18.79	21.02	25.25	24.69	26.17	28.49	26.34	27.50	28.17	28.60	29.53	319.43
23	Tomatoes	46	18.74	17.87	19.37	19.30	22.44	22.60	20.69	20.47	21.71	22.49	22.95	22.79	22.93	274.34
24	Wheat	35	21.34	25.32	24.65	28.06	25.43	29.08	23.33	26.53	29.16	26.53	25.37	30.68	27.31	342.81
25	Yams	28	54.47	50.90	50.98	54.52	63.50	64.06	69.84	71.18	77.11	75.99	79.81	84.72	86.58	883.66
	Total		**598.34**	**605.71**	**628.81**	**655.12**	**682.92**	**682.30**	**693.95**	**725.09**	**760.87**	**750.09**	**775.05**	**800.06**	**790.06**	**9148.36**

The residue potential of these crops can be determined by considering their gross potential, recoverable, economic, implementation, and sustainable biomass residue potentials [172] [173]. This study focused on analyzing the gross and recoverable residue potentials to assess the potential for solid biofuel, biogas, and bioethanol production. Due to socioeconomic and environmental issues, some biomass is not recoverable, while others are recoverable. The total agricultural yield determines the recoverable residue potential, representing a fraction of the gross residue. The ratio of the crop production determines the gross residue potential. The residue-to-product ratio (RPR) method [15] was deployed to estimate crop residue generation. RPR values for various crops and their corresponding calorific values were sourced from published literature. Table 4 presents the crop residues and their respective average RPR, recoverable fraction (RF), and lower heating values (LHV) for all the crop residues considered. Regarding the specific location under investigation, it is crucial to provide RPR, RF (%), and LHV (MJ/kg) estimations. Unfortunately, such statistical data are often not accessible both locally and globally. Therefore, this study has addressed this by determining the average RPR, RF (%), and LHV (MJ/kg) of the selected crops in Africa. **Table 10** displays the calculated average values for the recoverability factor (RF) and lower heating value (LHV). In addition, a new method was developed and used to assess the biomass energy potential of crop residues, aiming to accurately account for the wide range of diverse climatic and agricultural conditions. This study did not consider the socio-economic, sustainable, and socio-economic possibilities. Perhaps these factors may lower the overall predicted possibilities [70].

Table 10: Average RPR, RF, and LHV of selected crop residues widely considered for bioenergy production in Africa.

S/N	Energy Crops	Crop Residues (CR)	Average RPR	Average RF %	Average LHV (MJ/kg)	References
1	Bananas	Leaves, stems, and peels	2.1	0.9	12.1	[151], [174], [175], [176]
2	Barley	Straws	1.5	0.3	17.6	[153], [175]

3	Beans	Straws	2.2	0.9	13.5	[149], [176], [177]
4	Cabbages	Foliage and stem	2.5	1.0	1.0	[19]
5	Cashew	Husks	2.1	0.2	14.9	[154]
6	Cassava	Stems and peels	0.9	0.6	13.2	[148], [154], [174], [176], [178]
7	Coconuts	Fronds, Husks, shells	0.7	1.0	14.2	[148], [149], [154], [31], [174]
8	Cotton seed	Stalk	2.1	0.8	17.2	[148], [154], [151], [174], [178]
9	Groundnuts	Trash and shells	1.5	0.8	15.4	[148], [151], [154], [174], [175], [176], [178]
10	Lemons	Pruning	0.3	0.8	1.0	[175]
11	Lettuce	Foliage	1.2	0.5	15.2	[175]
12	Maize (corn)	Stalk and cobs	1.1	0.7	15.9	[151], [153], [154], [174], [175], [176], [177], [178]
13	Millet	Stalk and straws	2.0	0.7	15.5	[148], [151], [153], [154], [174], [175], [176], [178]
14	Oil palm	Kernel shell, fibre, fronds	0.3	1.0	14.3	[148], [70], [176]
15	Oranges	Peels	0.3	0.8	17.9	[151]
16	Pepper	Leaves	0.45	0.45	13.7	[179]
17	Potatoes	Leaves and peels	0.8	0.9	13.3	[151], [154], [174], [175], [176], [177], [178]
18	Rice	Straw and Husks	1.1	0.7	14.3	[148], [153], [174], [175], [178]
19	Sorghum	Stalk and straws	2.0	0.8	13.4	[148], [151], [153], [154], [174], [175], [176], [178]
20	Soya beans	Straw and pods	1.7	0.8	16.9	[153], [154], [174], [175], [176], [178],
21	Sugar cane	Bagasse and Leaves	0.2	0.8	15.4	[151], [154], [174], [175]
22	Sweet potatoes	Leaves and peels	0.5	0.8	13.3	[153], [174], [175], [176], [178]
23	Tomatoes	Stem and Leaves	0.2	0.5	13.7	[175]
24	Wheat	Straws and Husks	0.8	0.3	14.9	[153], [174], [175], [176]
25	Yams	Peels	0.3	0.7	10.6	[174], [175], [176], [178]

4.2.2 Estimation of the energy potential and feedstock from biomass waste

Crop residue potential estimation involves assessing the quantity remaining after agricultural production or post-harvesting processing. Agricultural residues are generally categorized as primary or secondary. Primary residues consist of materials generated during harvesting and initial crop processing in the farm which vary according to crop species and have been estimated to range from 19 % to 75% [176]. Secondary residues are generated by agricultural processing at specific locations or factories to achieve further byproducts of post-harvest processing. The recoverable crop residue potential is the quantity of crop residue that remains after being utilized for purposes such as feeds, organic fertilizer, fuel, or animal bedding [179]. On the other hand, the gross crop residue potential represents the total quantity of crop residue produced. The recoverable portion can be employed to produce bioenergy. Standard methods are used for the energy potential of recoverable residue biomass resources **(Fig. 8)**.

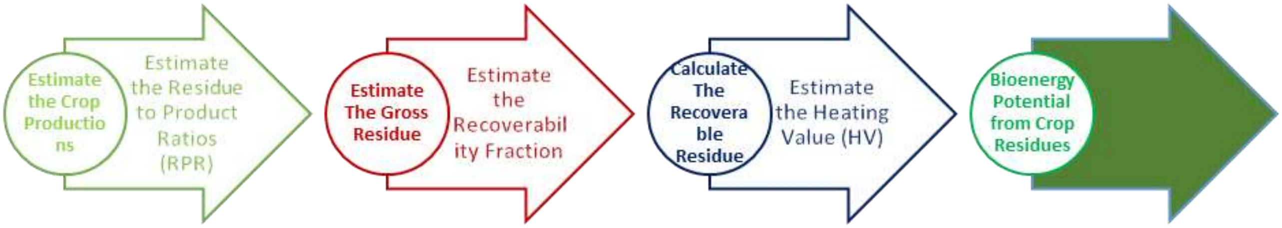

Fig. 8: Process flow diagram (PFD) for bioenergy potential determinations from crop residues

Gross Residue Potential (GRP) and Recoverable Residue Potential (RRP): The Gross residue potential for each crop, sometimes called the theoretical residue potential [70], was calculated by multiplying the total specific crop available (Eq. 1) for a particular year by the residue-to-product ratio (RPR). RPR represents the weight of residue a crop generates relative to the quantity produced [70], [180]. The crop residue potential was estimated using Eq. 2.

$$T_{cp(i)} = \sum_{i=1}^{k} A_{(i)} * Y_{(i)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

$$GRP_{(j)} = T_{cp_{(i)}} * RPR_{(i)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where $T_{cp(i)}$ is the total specific crop available or crop output at j^{th} location from a set of “k” crops, while A_i, Y_i, and RPR_i are the harvested area, average crop yield, and residue-to-product ratio of crop i^{th} at j^{th} location respectively. According to [70], utilizing the GRP for bioenergy production was not feasible due to potential competition with other crop residue uses [175], the need to rely on the recoverable residue fraction, known as the technical or recoverable residue potential (RRP) as in Eq. 3 [175].

$$RRP_j = \sum_{i=1}^{k} GRP_{(ij)} * RF_{(ij)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

where $GRP_{(ij)}$ is the residue potential at i^{th} location from a total k of crops, $RF_{(ij)}$ is the recoverability factor of the i^{th} crop at j^{th} location. The $RRP_{(j)}$ is the recoverable residue potential at location j^{th}. . This accounts for surplus residue considering the competition from other uses and spatial constraints as well as providing the number of excess residues available specifically for energy purposes. The RRP was used to estimate the energy potential of cellulosic bioethanol and biogas.

Solid Biofuel Potential: The bioenergy potential from dry crop residues in their natural state is determined according to **Eq. 4**. According to [175], the estimated SBP is calculated by multiplying the total recoverable residue potentials by their lower heating values (LHV) (**Eq. 4**).

$$BEP_{(Cj)} = \sum_{1=1}^{k} RRP_{(ij)} * LHV_{(ij)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

where $BEP_{(Cj)}$ is the bioenergy potential of ‘k’ crops at the j^{th} location,

$RRP_{(ij)}$ is the recoverable residue potential of the i^{th} crop at the jth location, and

$LHV_{(ij)}$ is the lower heating value of the i^{th} crop at the j^{th} location.

Similarly, [175], has shown that the estimated SBP can be derived by multiplying the total recoverable residue potentials by their lower heating values (LHV) (**Eq. 4**).

Bioethanol Potential (BEP): The bioenergy potential and conversion of crop residues into cellulosic ethanol were determined by considering pre-treatment processes such as hydrolysis, enzymatic activities, and microbial fermentation. The estimation of cellulosic ethanol production from crop residues was determined using **Eq. 5** [70].

$$Y_{BP} = RRP * C_{glu} * y_{hyd} * y_{eth} * \eta_{pre} * \eta_{enz} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. 5$$

where Y_{BP} = cellulosic ethanol yield; RRP = recoverable residue potential; C_{glu} = glucan concentration; y_{hyd} = yield of enzymatically hydrolyzed glucan; y_{eth} = stoichiometric yield from glucose; η_{pre} = efficiency of pretreatment; η_{enz} = efficiency enzymatic cellulose conversion. To estimate the cellulosic ethanol production, it is assumed that the fermentation and distillation processes had 100 % efficiency, suggesting no loss was considered. The accepted values [70], [172] for cellulosic ethanol production are shown in Table 4. In the scenario where no pre-treatment was performed, enzymatic activity was believed to be minimal (~ 30 %), resulting in a cellulosic ethanol scale-up (η_{scale}) of ~ 50 %. In contrast, the pre-treatment scenario assumed an enzymatic efficiency of 90 %, leading to a cellulosic ethanol yield of 80 %. The bioenergy potential of cellulosic ethanol was estimated based on a lower heating value (LHV) of 28.9 MJ/kg and an ethanol density of 0.789 kg/L [70].

Table 11: Assumptions used in the calculations

Conditions	*Buswell Glucan yield (L CH4/g)*	*Buswell hemicellulose yield (L CH4/g)*	y_{eth}	y_{hyd}	η_{pre} *(%)*	η_{enz} *(%)*	ρ_{Distil} *(%)*	P_{Ferm} *(%)*	η_{scale} *(%)*	*Ethanol Density (kg/l)*
Pre-treatment	0.414	0.423	0.51	1.11	-	30	100	100	50	0.789
No pre-treatment	0.414	0.423	0.51	1.11	80	90	100	100	80	0.789

Biogas Potential (BGP)*:* Biogas was estimated using the gross residue potential derived from crop residues. The biomethane potential (BMP) was calculated using the Buswell BMP equivalent, representing the gross methane production estimate based on the experimental evaluation. The BMP quantifies the maximum methane volume generated per gram of volatile solid (VS) in a substrate, indicating its biodegradable fraction.

Several assumptions were made to calculate the energy potential of biogas: it is assumed that each cubic meter (m^3) of biomethane would yield 10 kWh at standard temperature and pressure (STP). The methane conversion process has an energy potential of 0.278 gigawatt-hours per year (GWh/yr). To convert this energy from terajoules (TJ) to million tonnes of oil equivalent (Mtoe), a conversion factor of 24 is considered [70].

$$\gamma_{BMP\ Buswell} = \left(\gamma_{Buswell,glu} * C_{glu}\right) + \left(\gamma_{Buswell,hem} * C_{hem}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

The maximum biogas potential estimate is determined (Eq. 7)

$$\gamma_{Biogas} = RRP * \gamma_{BMP\ Buswell} * \eta_{scale} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

where $Y_{BMP\ Buswell}$ = estimated biodegradable fraction in specific crop residue (feedstock) for biogas production using Buswell formula; $Y_{Buswell.glu}$ = estimated glucan in specific residue using Buswell formula; $Y_{Buswell.hem}$ = estimated hemicellulose using Buswell formula; C_{glu} = concentration of glucan; C_{hem} = concentration of hemicellulose. Y_{Biogas} = biogas yield; η_{scale} = average efficiency for continuous biogas production.

4.2.3 Case Studies

The bioenergy potentials of 15 selected countries (Algeria, Morocco, Egypt, Nigeria, Ivory Coast, Ghana, Sudan, Democratic Republic of Congo, Ethiopia, Kenya, Mozambique, South Africa, Namibia, Angola, and Central African Republic) from the five regions of Africa (**Fig. 9)** were analyzed based on the country's significant agricultural activities, available data, and potentials for using biomass for energy purposes. These estimates were also based on the 25 selected crops and production year (2010 – 2022).

Fig. 9: Map showing the 15 selected countries based on regions and agricultural activities.

4.3 Results and Discussions

4.3.1. Crop Production and Residues Potentials

An assessment was conducted to determine Africa's capacity to produce bioenergy from various feedstock sources. This was done by evaluating the total production of the 25 selected crops. This was calculated by multiplying the crop yields by the harvested areas in various regions of Africa. The average ratios of residue to product (RPR) were calculated for these locations. The crop residues (CR) considered were the leaves, stems, foliage, fronds, straws, stalks, cobs, pods, shells, peels, and husks from the harvesting and processing activities. These values were used to determine the energy capacity of the crop residues and, consequently, the biomethane and cellulosic ethanol yields. To guarantee a sustainable supply of biomass feedstocks for bioenergy production, estimating the quantity of recoverable crop residues is essential.

Fig. 10 shows the residues projections for 2023, 2024, and 2025. It showed cassava will grow to 223.56, 218.48, and 223.43 Mt for 2023, 2024, and 2025 respectively. Barley had a decrease in 2024 (8.39 Mt) and 2025 (13.78 Mt) when compared to 2023 (15.64 Mt) projections. Maize and Sugarcane also recorded low production rates in 2023, 2024, and 2025 at an average 0.2 % growth rate. This could be inferred due to climate change impacts and political or tribal unrest in regions known for high production of these agricultural products.

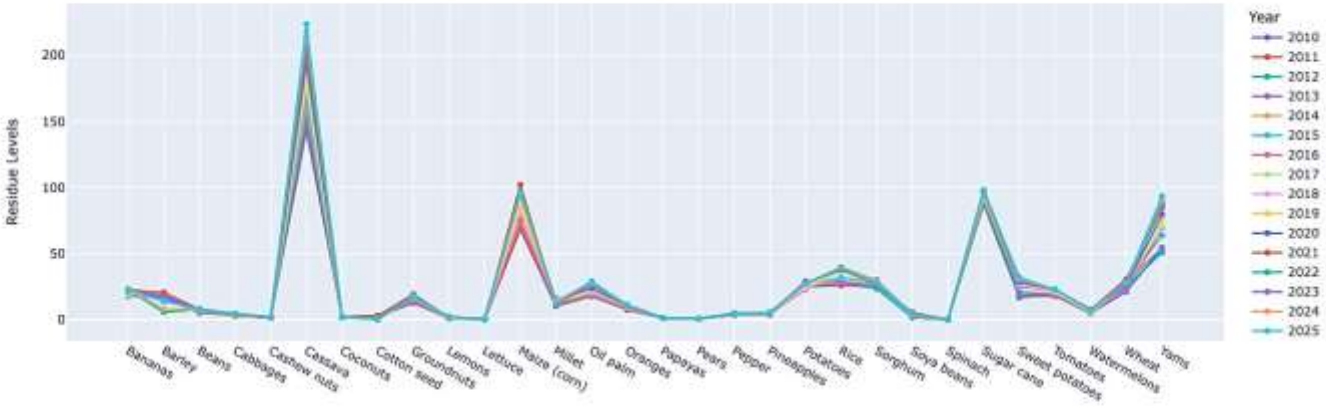

Fig. 10: The crop residues projections

In **Table 12**, the crop production has increased steadily from 598.34 Mt in 2010 to a peak of 800.06 Mt in 2021. Correspondingly, the gross residue potential grew from 525.18 Mt in 2010 to 691.45 Mt in 2021. These potentials can be utilized to produce solid biofuels such as briquettes and pellets, as well as for the generation of biogas, bioethanol, or a combination of these. The solid biofuel potential increased from 120.57 Mtoe/year to 157.72 Mtoe/year. **Table 15 -17** showed that Nigeria and Egypt have the highest potential for solid biofuel production with consistent growth and high averages. Ivory Coast, Ghana, Ethiopia, and DRC also showed steady growth in crop production over the years, while CAR and Namibia revealed relatively low and stable production values. By region, North Africa’s output id heavily reliant on Egypt. Nigeria and Ghana in Western Africa with robust growth, DRC and moderate growth in Sudan and CAR for the Central and Northeastern Africa. Ethiopia dominates in the Eastern and Southeastern region, while Southern Africa's production is driven by the Republic of South Africa.

4.3.2 Cellulosic Ethanol and Biomethane Production

The estimated average cellulosic ethanol production (**Table 13**) for the investigative period is 114,400 ML per annum (62.62 Mtoe/year) with the highest production recorded in 2021. The average biomethane production is 9,621 Mm^3CH_4/year (83.06 Mtoe/year). However, residues from cassava, maize, and cereal crops recorded a significant quantity of solid biofuel, biomethane, and bioethanol potentials. In **Table 13,** the biomethane production grew from 8,247.85 Mm^3 CH_4/year in 2010 to 11,055.35 Mm^3 CH_4/year in 2021, while its energy equivalent increased, from 71.20 Mtoe/year to 95.44 Mtoe/year. Bioethanol production also increased from 98,629.02 ML/year in 2010 to 131,263.33 ML/year in 2021, while the energy equivalent increased from 53.97 Mtoe/year to 71.83 Mtoe/year during the same period. These increasing trends show a growing capacity for bioenergy production and support for energy security in Africa and could reduce fossil fuel dependencies. In **Table 13,** the highest gross residue potentials were bananas (543.07 Mt/year), cassava (2141.72 Mt/year), maize (1139.46 Mt/year), and sorghum (693.05 Mt/year). The biomethane potential showed highest values with maize (corn), cassava, sorghum and banana at 569,865.59, 254,661.19, 112,668.76, and 90,845.18 Mm^3 CH_4 respectively. The highest bioethanol production potential was maize (corn): 284,251.24 ML/year), cassava (151,172.27 ML/year), sorghum (71,142.32 ML/year), and bananas (54,402.80 ML/year). These infer that both cassava and maize are the promising crops for bioenergy production across all categories (solid biofuel, biomethane, and bioethanol). However, the sorghum and bananas indicated significant potential, particularly in terms of biomethane and bioethanol production. Other crops like groundnuts, potatoes, and rice revealed substantial contributions, especially for solid biofuel and biomethane, while crops with lower residue and energy potential include lemons, lettuce, and tomatoes. The **Table 18** showed that Southern Africa consistently leads in Biomethane production, followed by Northern Africa and Western Africa. Central/Northeastern Africa and Eastern/Southeast Africa generally have lower production levels. Nigeria stands out as a significant contributor to biomethane production, showing substantial growth over the years. On average, Southern Africa has the highest biomethane production at 7.48 Mtoe, followed by Western Africa (6.33 Mtoe) and Northern Africa (0.66 Mtoe). The percentage change from 2010 to 2022 varies across regions, with notable increases in some areas like Southern Africa (9%) and Nigeria (15%). **Fig. 11** revealed that Nigeria, South Africa, and Ethiopia dominate bioethanol production in Western Africa, Southern Africa and Central/Northeastern Africa with substantial growth from 2010 to 2022. Furthermore, all the 15 countries contributed more than 50 % of Africa's bioenergy potential for the period under investigation. Southern Africa consistently has the highest bioethanol production among the regions (**Table 19**). These data reflect a promising shift towards renewable energy, particularly in biomethane production, across various African regions, with notable differences in growth rates and production levels between countries.

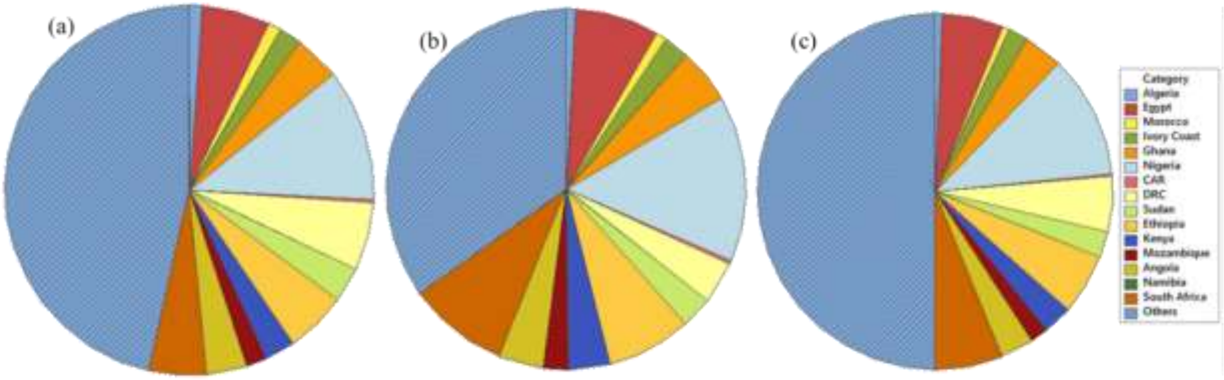

Fig. 11: Potential distribution of (a) solid biofuel, (b) Biomethane and (c) Bioethanol

Fig. 12a shows that Nigeria, Ghana, and DRC witnessed significant and continuous increases in crop production compared to other countries. Namibia and CAR are the lowest, with no substantial increase. The residue production from the crops is potential feedstock for biofuel production and, therefore, significant in the bioenergy value chain. The production profiles for solid biofuel potential (**Fig. 12b**), biomethane potential (**Fig. 12c**), and bioethanol potential (**Fig. 12d**) for the various countries were evaluated. **Fig. 12d** also showed clear and distinct variations in bioethanol production potential in South Africa, which is now leading in Africa.

Table 12: Total annual crop yield and Bioenergy equivalent for 2010 to 2022

Year	Crop Production	Gross Residue Potential	Solid Biofuel		Biomethane		Bioethanol	
	Mt	Mt	Mt/year (Recoverable)	Mtoe/year	Mm^3 CH_4/year	Mtoe/year	ML/year	Mtoe/year
2010	598.34	525.18	360.60	120.57	8,247.85	71.20	98,629.02	53.97
2011	605.71	525.94	358.32	119.73	8,206.50	70.85	99,005.77	54.18
2012	628.81	548.73	374.86	125.53	8,630.62	74.51	104,468.69	57.17
2013	655.12	568.90	388.21	129.70	8,855.89	76.45	107,039.08	58.58
2014	682.92	594.22	407.42	136.59	9,399.33	81.15	111,652.32	61.10
2015	682.30	592.06	402.38	134.48	9,159.33	79.07	109,003.99	59.65
2016	693.95	605.35	414.95	138.55	9,415.88	81.29	110,695.16	60.58
2017	725.09	631.86	431.63	144.90	10,068.41	86.92	119,274.26	65.27
2018	760.87	665.68	452.48	151.61	10,382.47	89.63	122,196.63	66.87
2019	750.09	649.63	443.43	148.38	10,207.92	88.13	120,870.21	66.15
2020	775.05	673.49	462.94	154.93	10,759.77	92.89	127,586.13	69.82
2021	800.06	691.45	471.97	157.72	11,055.35	95.44	131,263.33	71.83
2022	790.06	672.49	467.37	154.59	10,691.13	92.30	125,522.48	68.69
Average	703.72	611.15	418.20	139.79	9,621.57	83.06	114,400.54	62.61

Mt: Million tonnes, Mtoe: million tonnes of oil equivalent, Mm3 CH4/year: Million cubic meters of methane per year, ML/year: Million liters per year.

Table 13: Bioenergy potential by crops residues

Crops	**Residues**	**Crop Production**	**Gross Residue Potential**	**Solid Biofuel**		**Biomethane**		**Bioethanol**	
		Mt	**Mt**	**Mt/year (Recoverable)**	**Mtoe/year**	**Mm3 CH4/year**	**Mtoe/year**	**ML/year**	**Mtoe/year**
Bananas	Leaves, stem and peels	261.37	543.07	481.00	139.40	90845.18	78.43	54402.80	47.82
Barley	Straws	235.88	359.71	106.12	44.70	22048.37	19.03	14972.61	13.16
Beans	Straws	89.16	195.27	166.63	54.15	29957.21	25.86	16418.68	14.43
Cabbages	Foliage and stem	43.58	108.95	103.50	2.48	7553.36	6.52	6790.07	5.97
Cashew	Husks	23.05	48.41	8.23	2.94	1300.61	1.12	820.22	0.72
Cassava	Stems and peels	2287.18	2141.72	1181.69	373.62	254661.19	219.85	151172.27	132.89
Coconuts	Fronds, Husks, shells	27.74	18.31	18.31	6.24	6308.20	5.45	2425.65	2.13
Cotton seed	Stalk	31.87	65.86	55.10	22.75	17530.77	15.13	16478.97	14.49
Groundnuts	Trash and shells	210.37	306.45	249.98	92.13	76174.21	65.76	58604.26	51.52
Lemons	Peels	18.67	5.60	4.48	0.11	704.65	0.61	522.28	0.46
Lettuce	Foliage	5.85	7.02	3.51	1.28	882.32	0.76	366.73	0.32
Maize (corn)	Stalk and cobs	1074.41	1139.46	833.08	318.28	569865.59	491.97	284251.24	249.88
Millet	Stalk and straws	172.77	336.90	240.55	89.62	34862.03	30.10	20809.08	18.29
Oil palm	Kernel shell, fiber, fronds	276.25	72.93	72.93	25.00	39564.76	34.16	21475.85	18.88
Oranges	Peels	121.12	35.73	28.58	12.25	1887.51	1.63	846.59	0.74
Pepper	Leaves	55.79	55.79	55.79	32.14	9275.33	8.01	628.00	0.55
Potatoes	Leaves and peels	338.88	263.48	223.96	71.50	52955.37	45.72	42492.84	37.35
Rice	Straws	437.58	467.77	317.38	108.55	50288.16	43.41	36356.40	31.96
Sorghum	Stalk and straws	353.29	693.05	582.16	186.83	112668.76	97.27	71142.32	62.54
Soya beans	Straw and pods	41.47	69.01	57.96	23.48	8885.23	7.67	6151.45	5.41
Sugar cane	Bagasse and Leaves	1221.84	293.24	234.59	86.96	52513.36	45.34	30177.22	26.53
Sweet potatoes	Leaves and peels	319.43	159.72	127.77	40.80	14691.86	12.68	8135.93	7.15
Tomatoes	Stem and Leaves	274.34	54.87	27.43	9.02	4404.76	3.80	2587.66	2.27
Wheat	Straws and Husks	342.81	259.68	76.61	27.44	14661.12	12.66	8622.52	7.58
Yams	Peels	883.66	243.01	179.22	45.61	34764.50	30.01	16725.54	14.70
	Average	**365.93**	**317.80**	**217.46**	**72.69**	**60370.18**	**52.12**	**34935.09**	**30.71**

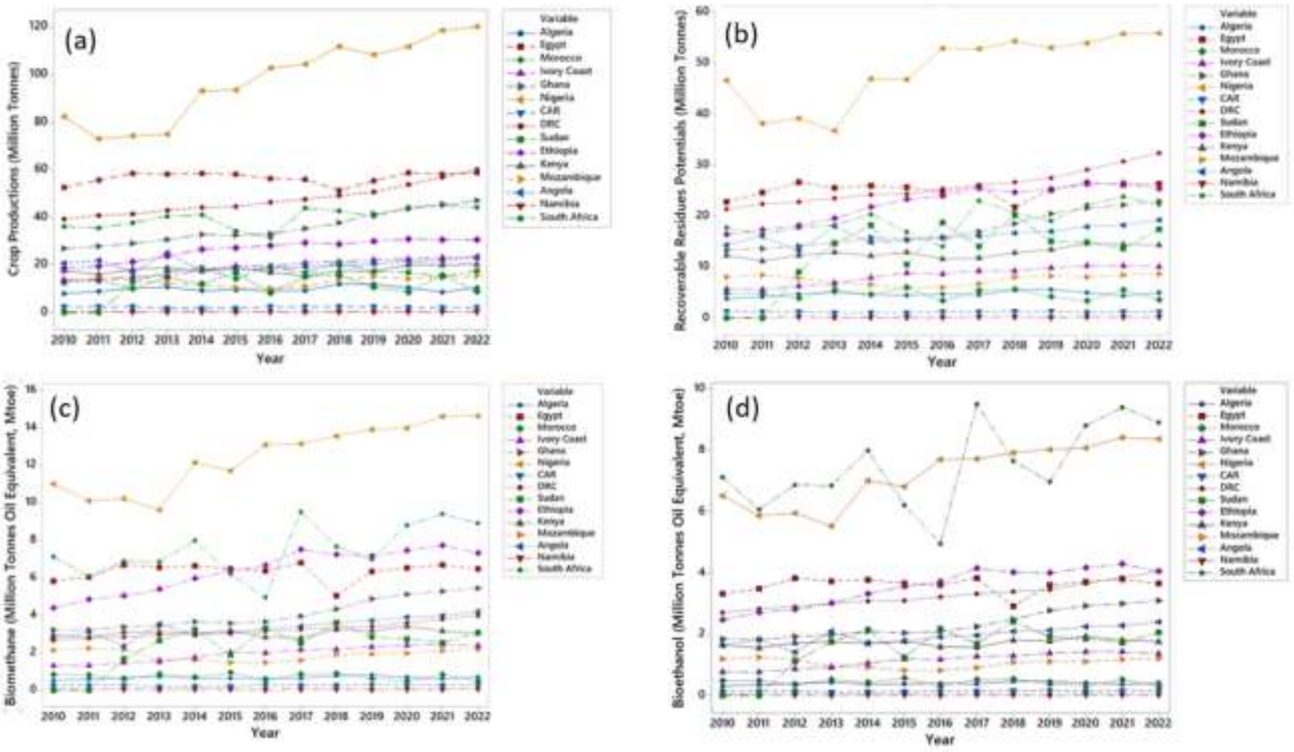

Fig. 12: Profiles of (a) Crop productions by countries, (b) Recoverable residues potential (solid biofuel potential) by countries, (c) Biomethane potential by countries, (d) Bioethanol potentials (BEP) by countries

4.3.3 Discussions

The results showed that Africa has enormous energy potential in the form of biomass-generated energy that could address the rural energy poverty mainly in the rural areas when scaled up. The 15 selected countries by region, out of the 55 African countries, made significant contributions of over 50 % towards their energy potentials. This implies that developing bioenergy at regional levels can effectively contribute to economic growth in the respective regions. Although Africa contributes about 4 % of global emissions, it disproportionately experiences negative impacts such as drought, desert encroachment, flooding, diseases, and inter-tribal crises due to the migration of herders. These factors significantly affect agricultural production and hinder the development of bioenergy. On the other side are insecurities and insurgencies. Therefore, there is a need to strengthen the security of architecture continently, thereby strengthening the agricultural sector, not just for food security but also to extract the addition of energy value, including biomass residue collection, processing, transportation, logistics, storage, and financing.

Rural areas in Africa have a higher incidence of poverty, primarily because most of the population are into semi-mechanized agriculture. However, providing education on residue collecting and processing for bioenergy generation is crucial for improving the farmers' livelihood. Moreover, these activities would necessitate substantial infrastructure investments for road networks, transportation systems, irrigation and water supply, and power supply. Effective policies and robust research and development are essential value chain components. They can process these residues by gasification for synthesis gas (syngas), pyrolysis for biochar and bio-oils, fermentation for liquid biofuel, briquetting, or pelletization for solid biofuels.

Bioenergy is a versatile and adaptable solution that can facilitate Africa’s climate neutrality by 2050 and create employment opportunities and foster economic growth. Its impact on income, employment, and food security has recently attracted broad discussions. The production of bioenergy can yield both positive and negative environmental consequences, and these can vary based on factors such as the type of biomass utilized, geographical locations of some useful land, and the methods of management employed [181]. By reducing reliance on fossil fuels, biofuels contribute to GHG emission reductions and environmental pollutant mitigations. They also enhance the local economy by creating employment opportunities. Moreover, the bioeconomy plays a crucial role in waste management, utilizing various waste streams such as agricultural residue, municipal solid waste (MSW), and industrial waste to produce biofuels and other high-value products. This addresses waste disposal challenges and creates new employment opportunities across the biofuel production and processing sectors. While the bioeconomy may have some adverse effects, its benefits for environmental sustainability and human welfare are substantial and can be effectively managed for long-term sustainability [182].

Africa has progressively developed in food and bioenergy crop cultivation since the 2000s, which poses challenges toward its transition to a bioeconomy [183]. In Europe, each additional Mtoe of biomass for energy could impact ~ € 359 million in terms of GDP and ~ 7,376 full-time equivalent employment creation while mitigating ~2.4 $MtCO_2eq$ emissions due to the transition from fossil energy [184]. Various innovative technologies and tools have emerged in Africa to produce and distribute renewable bioenergy. These technologies promote the sustainable use of locally available resources without disrupting food and water supply [185]. Researchers have identified three primary challenges in rural bioenergy for Africa: the use of unsustainable bioenergy feedstock resulting in deforestation, inefficient domestic energy production systems, and the absence of mechanisms to guarantee the sustainability of improved bioenergy solutions, mainly through research and development [186]. South Africa has witnessed the implementation of waste-to-energy systems in rural and underserved municipalities, notably micro-bio-digesters, and these have been instrumental in advancing sustainable development goals by enhancing livelihood [187]. The South African government has implemented various measures to encourage the commercial production of biofuels, such as exempting biofuels from existing fuel levies. Prospective biodiesel producers were granted a 50 % exemption from fuel levies, while prospective bioethanol producers received a 100 % exemption [188]. In Zambia, Sunbird Bioenergy has set up a biorefinery in Luapula that uses cassava as a feedstock to produce 120 m liters of bioethanol per annum [186]. This production delivers 20 % of Zambia's petroleum consumption, reducing its import bill by $100 m [186].

4.3.4 Future Perspectives: Overcoming the Barriers to Bioenergy Production in Africa

Africa faces several barriers that hinder bioenergy solutions' development and widespread adoption [189]. The continent can unlock its bioenergy potential by addressing these challenges and contributing to energy security, economic development, and environmental sustainability [190]. Collaboration among governments, industries, academia, and communities is essential to realize the full benefits of bioenergy and drive the continent towards a sustainable energy future [191]. Overcoming these challenges requires a robust approach integrating technological advancements, monetary incentives, social engagement, institutional capacity, and supportive policies. In Zambia for instance, the barriers to biogas technology adoption were identified non-beneficiaries and private sector representatives to be due to institutional, situational, technical, and dispositional factors [192]. The study recommended the Zambian government to strengthen institutional infrastructure, focus on renewable energy policies, foster public-private partnerships, encourage research and development (R&D), stabilize the market, improve coordination, and boost public awareness to enhance clean energy provision. **Table 13** shows, but is not limited to, the mitigations and solutions to the barriers.

Table 14: Barriers and solutions to Bioenergy Production [193], [194], [195]

Barriers to Bioenergy Production		**Mitigation Measures/Solutions**
Categories	**Barriers**	
Financial Barriers	1. A high initial capital outlay is required. 2. Limited access to loans and financial support. 3. Long payback periods for household-level biogas digesters.	1. Reliable information dissemination on bioenergy technology with local authorities, politicians, and the public. 2. Financial institutions should provide loans for bioenergy projects. 3. Subsidies for pilot and demonstration projects to enhance adoption. 4. Offer partnerships with private companies for biogas technology production. 5. Promote community-level biogas digesters to reduce payback periods through shared resources and labor.
Technological Barriers	1. Lack of knowledge and technical skills. 2. Inadequate design adapts to local needs. 3. Dependence on imported materials and prefabricated systems. 4. Limited follow-up services post-installation.	1. Knowledge Transfer among bioenergy projects and between research institutions and practitioners. 2. Provide training for skilled labor, owners, operators, and technicians in biogas technology. 3. Support research to optimize production and improve technology. 4. Train and employ technicians for post-

		installation services and encourage user engagement. 5. Provide operation and maintenance manuals in local languages.
Socio-Cultural Barriers	1. Lack of awareness and understanding of bioenergy technology. 2. Social perception and resistance to new technology.	1. Conduct educational and awareness programs through pamphlets, community meetings, and media. 2. Encourage penning of livestock for effective dung collection.
Institutional Barriers	1. Inadequate institutional support and frameworks. 2. Insufficient government commitment to renewable energy	1. Introducing policies, legislation, and financial subsidies to support biofuel adoption. 2. Establish national frameworks to support bioenergy system implementation. 3. Promote government commitment to renewable energy programs and sources.
Policy and Regulatory Barriers and Solutions	1. Complicated or insufficient regulatory frameworks that create obstacles for biogas projects	1. Streamlining regulations to make it easier to start and maintain biogas projects 2. Implement coherent and consistent policies to support the development of bioenergy energy
Environmental and Sustainability Considerations	1. Limited availability of raw materials for biodiesel production. 2. The conflict between using agricultural resources for food versus fuel production.	1. Develop sustainable agricultural practices and diversify feedstock sources. 2. Implement policies to balance agricultural resources between food and fuel production.

4.3.5 Achieving Circular Economy in Africa through Bioenergy

Utilizing crop residues for biofuel production aligns with circular economy principles, promoting sustainability. The principles and models of circular economy aim to minimize waste and make the most of resources (**Fig. 13**). It can also optimize energy transition [196]. In Africa, where waste management and energy access are significant challenges, leveraging bioenergy can drive both environmental and socio-economic benefits, fostering a more sustainable and circular economy [197]. Africa's vast agricultural lands generate substantial biomass residues, which can be harnessed for bioenergy production. Key sources include forest residues, crop residues, animal manure, and organic municipal solid waste (MSW). Transforming these resources into energy can reduce reliance on fossil fuels, decrease greenhouse gas emissions, and enhance energy security. Achieving a circular economy in Africa through bioenergy is both a viable and necessary endeavor. By transforming waste into valuable energy, Africa can address its energy and waste management challenges, drive economic growth, and promote environmental sustainability. Collaboration among governments, the private sector, academia, and communities is essential to harness the full potential of bioenergy and realize a sustainable future for the continent [193]. There should be a continent-wide investment portfolio on bioenergy to be driven by the African Union, regional bodies, Afrexim Bank, and the African Development Bank as well as donor agencies like the U.S. Agency for International Development (USAID), International Development Research Centre (IDRC), and Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

Fig. 13: Key Components of Achieving Circular Economy through Bioenergy

4.4 Conclusions

This study evaluated the potential role of solid biofuel, biogas, and bioethanol from 25 energy crops to meet the energy demand of Africa in 15 selected countries within the continent for 13 years. The feedstock considered was limited to crop residues, while the forestry, animal dung, and municipal solid wastes (MSW) were excluded. The result demonstrated that the residues can sustainably generate modern energy for Africa. For the time frame analyzed, African bioethanol production averaged 62.62 Mtoe, 83.05 Mtoe of biomethane, and 139.79 Mtoe solid biofuel annually. Maize (corn) exhibited the highest bioenergy potential among the crops, followed by cassava and sorghum. Three countries were regionally selected based on their agricultural and bioenergy activities and evaluated for their bioenergy potential. The result showed that South Africa and Nigeria have the most potential, while Namibia and CAR demonstrate the lowest potential. The quantity of bioenergy produced depends on crop production, recoverable residue-to-product ratio, the lower heating value of the crops, and biochemical compositions such as starch, cellulose, hemicellulose, and lignin. Furthermore, to comprehensively understand the challenges that prevent the widespread implementation of bioenergy in Africa, it is necessary to carry out socioeconomics, technology, environment, and risk assessments.

Africa accounts for only about 4 % of global greenhouse gas emissions, the lowest of any continent, yet it suffers disproportionately from the impacts of climate change. Additionally, the continent faces significant energy poverty, exacerbating its vulnerability. Due to the lack of electricity and clean cooking facilities, ~600 million and ~900 million of its population are deprived of these basic needs. Thus, this has significantly hindered both economic progress and human capital development. This study provided a comprehensive assessment of the energy potential associated with selected agricultural residues in Africa, focusing on promoting circular economy principles through bioenergy production. The study also examined the possible countries chosen based on their farming productions and bioenergy activities. The crop production data was acquired from the United Nations Food and Agricultural Organization Statistics (**FAOSTAT**) database, while other necessary data were obtained from the literature and analyzed. By analyzing various crop residues and residual biomass sources, their suitability for bioenergy generation and contribution to sustainable resource utilization were evaluated.

Through a combination of empirical data analysis and modeling techniques, we accurately measure the energy potential of crop residues and highlight their role in promoting circular economy practices. The findings of this study offer valuable information on the feasibility and viability of utilizing agricultural residues for bioenergy production, offering potential solutions to address energy challenges while fostering environmental sustainability in Africa.

Mt: Million tonnes, Mtoe: million tonnes of oil equivalent, PJ/year: petajoules per year, Mm3 CH4/year: Million cubic meters of methane per year, ML/year: Million liters per year.

Table 15: Crop productions of selected Countries by regions

Year	**Crop Productions (Million Tonnes)**														
	Northern Africa			**Western Africa**			**Central/Northeastern Africa**			**Eastern/ Southeast Africa**			**Southern Africa**		
	Algeria	**Egypt**	**Morocco**	**Ivory Coast**	**Ghana**	**Nigeria**	**CAR**	**DRC**	**Sudan**	**Ethiopia**	**Kenya**	**Mozambique**	**Angola**	**Namibia**	**South Africa**
2010	8.11	52.68	12.76	13.81	26.88	82.28	2.38	39.30	0.00	18.53	17.45	13.35	20.58	0.15	36.32
2011	9.00	55.63	13.54	13.90	27.84	73.16	2.27	40.73	0.00	19.37	16.12	14.54	22.08	0.15	35.58
2012	10.23	58.60	10.07	15.02	28.90	74.38	2.33	41.59	12.91	21.20	18.26	13.26	17.03	0.19	37.83
2013	10.76	58.19	14.93	15.54	30.74	74.92	1.80	43.02	17.17	23.74	18.72	12.32	24.89	0.11	40.49
2014	9.21	58.41	11.86	17.98	32.84	93.28	1.91	44.31	18.75	26.56	17.45	11.71	17.53	0.14	41.04
2015	9.41	58.21	16.73	19.86	32.40	93.54	1.90	44.52	14.11	27.16	19.08	10.38	17.89	0.15	34.46
2016	9.24	56.24	8.33	19.53	33.20	102.89	2.38	46.48	19.37	28.24	17.06	10.30	18.64	0.11	31.48
2017	9.24	56.14	15.05	21.06	35.30	104.40	2.39	47.65	16.74	29.45	15.31	11.19	19.01	0.17	44.08
2018	11.97	51.35	15.76	21.43	37.76	111.75	2.47	49.07	21.01	28.70	17.51	14.22	19.82	0.18	42.55
2019	11.99	55.44	10.81	22.33	41.43	108.30	2.54	50.62	17.15	30.04	17.13	14.98	20.34	0.09	40.57
2020	10.41	58.78	8.52	22.67	43.49	111.83	2.11	53.96	16.90	30.86	20.13	14.07	21.53	0.20	44.36
2021	8.53	58.08	15.58	23.08	45.62	118.57	2.16	57.09	15.07	30.46	20.10	14.85	22.03	0.19	45.09
2022	10.38	58.70	8.99	23.23	47.00	120.10	2.20	60.13	17.51	30.48	20.38	15.54	23.35	0.21	44.22
Average	**9.88**	**56.65**	**12.53**	**19.19**	**35.65**	**97.65**	**2.22**	**47.57**	**14.36**	**26.52**	**18.05**	**13.13**	**20.36**	**0.16**	**39.85**

Table 16: Recoverable Residues Potentials of the selected energy crops by countries (regions)

Year	**Recoverable Residues Potentials (Million Tonnes)**														
	Northern Africa			**Western Africa**			**Central/Northeastern Africa**			**Eastern/ Southeast Africa**			**Southern Africa**		
	Algeria	**Egypt**	**Morocco**	**Ivory Coast**	**Ghana**	**Nigeria**	**CAR**	**DRC**	**Sudan**	**Ethiopia**	**Kenya**	**Mozambique**	**Angola**	**Namibia**	**South Africa**
2010	3.73	22.82	4.82	5.68	13.37	46.61	1.31	21.35	0.00	16.35	12.34	8.00	14.32	0.14	17.75
2011	4.15	24.62	4.82	5.59	13.61	38.13	1.25	22.34	0.00	17.26	11.22	8.45	16.08	0.14	16.34
2012	4.70	26.60	3.84	6.34	14.14	39.20	1.27	22.75	9.06	18.14	12.31	7.80	13.23	0.19	17.68
2013	5.09	25.54	5.48	6.73	14.74	36.67	0.98	23.50	14.70	19.49	12.95	7.03	18.00	0.10	18.21
2014	4.54	25.93	4.56	7.93	15.81	46.93	1.02	24.23	18.19	21.78	12.17	6.48	14.83	0.14	20.30
2015	4.53	25.59	5.97	8.83	15.51	46.75	1.02	24.30	10.46	23.32	12.91	5.88	15.23	0.14	16.91
2016	4.65	24.73	3.39	8.61	15.84	52.85	1.27	25.34	18.76	23.93	11.65	6.02	15.69	0.09	13.99
2017	4.56	25.81	5.41	9.31	16.94	52.75	1.27	26.00	14.01	25.42	11.81	6.74	16.07	0.17	22.98
2018	5.45	21.80	5.59	9.31	18.50	54.28	1.33	26.69	20.14	24.66	12.81	8.08	16.67	0.20	20.64
2019	5.56	25.14	4.14	9.92	20.45	53.00	1.36	27.42	15.07	25.20	13.46	8.22	17.01	0.08	19.05
2020	4.97	26.51	3.41	10.25	21.53	53.89	1.16	29.05	14.88	26.29	14.61	7.99	17.88	0.21	22.16
2021	4.36	26.15	5.53	10.23	22.16	55.77	1.19	30.71	13.65	26.46	14.40	8.41	18.19	0.18	23.80
2022	4.94	26.37	3.58	10.06	22.92	55.79	1.21	32.38	17.41	25.34	14.33	8.64	19.21	0.18	22.25
Average	**4.71**	**25.20**	**4.66**	**8.37**	**17.35**	**48.66**	**1.20**	**25.85**	**12.79**	**22.59**	**12.84**	**7.52**	**16.34**	**0.15**	**19.39**

Table 17: Solid Biofuel Potentials by countries (regions)

Year	Solid Biofuel Potentials (Million Tonnes Oil Equivalent, Mtoe)														
	Northern Africa			**Western Africa**			**Central/Northeastern Africa**			**Eastern/ Southeast Africa**			**Southern Africa**		
	Algeria	**Egypt**	**Morocco**	**Ivory Coast**	**Ghana**	**Nigeria**	**CAR**	**DRC**	**Sudan**	**Ethiopia**	**Kenya**	**Mozambique**	**Angola**	**Namibia**	**South Africa**
2010	1.26	7.49	1.68	1.84	4.38	15.66	0.41	6.87	0.00	5.42	3.55	2.70	4.27	0.05	6.44
2011	1.38	8.14	1.72	1.81	4.44	12.74	0.39	7.19	0.00	5.74	3.38	2.86	4.79	0.05	5.91
2012	1.56	8.68	1.26	2.07	4.62	13.11	0.40	7.32	3.02	6.04	3.79	2.66	3.86	0.06	6.43
2013	1.68	8.53	1.89	2.20	4.79	12.14	0.30	7.57	4.92	6.53	3.80	2.34	5.43	0.03	6.62
2014	1.47	8.68	1.55	2.58	5.13	15.60	0.32	7.81	6.05	7.32	3.67	2.18	4.40	0.05	7.40
2015	1.49	8.51	2.11	2.87	5.03	15.49	0.32	7.83	3.47	7.81	3.83	1.96	4.53	0.05	6.12
2016	1.49	8.27	1.13	2.79	5.14	17.55	0.40	8.17	6.24	8.05	3.37	2.02	4.74	0.03	5.03
2017	1.48	8.66	1.89	3.03	5.51	17.53	0.40	8.38	4.67	8.64	3.39	2.25	4.84	0.06	8.44
2018	1.82	7.22	1.97	3.04	6.02	17.95	0.41	8.60	6.83	8.29	3.82	2.69	5.05	0.07	7.54
2019	1.83	8.36	1.40	3.22	6.67	17.61	0.43	8.84	5.09	8.50	3.88	2.75	5.15	0.02	6.90
2020	1.61	8.87	1.11	3.32	7.02	17.90	0.37	9.36	5.08	8.86	4.19	2.67	5.42	0.07	8.10
2021	1.35	8.77	1.91	3.32	7.20	18.48	0.38	9.89	4.57	8.88	3.98	2.82	5.54	0.06	8.71
2022	1.60	8.80	1.16	3.23	7.45	18.43	0.38	10.42	5.82	8.50	3.76	2.89	5.85	0.06	8.08
Average	**1.54**	**8.38**	**1.60**	**2.72**	**5.65**	**16.17**	**0.38**	**8.33**	**4.29**	**7.58**	**3.72**	**2.52**	**4.91**	**0.05**	**7.06**
	1%	**6%**	**1%**	**2%**	**4%**	**12%**	**0%**	**6%**	**3%**	**5%**	**3%**	**2%**	**4%**	**0%**	**5%**

Table 18: Biomethane Biofuel Potentials by countries (regions)

Year	Biomethane (Million Tonnes Oil Equivalent, Mtoe)														
	Northern Africa			Western Africa			Central/Northeastern Africa			Eastern/ Southeast Africa			Southern Africa		
	Algeria	Egypt	Morocco	Ivory Coast	Ghana	Nigeria	CAR	DRC	Sudan	Ethiopia	Kenya	Mozambique	Angola	Namibia	South Africa
2010	0.53	5.81	0.82	1.33	3.20	10.99	0.26	2.64	0.00	4.38	2.94	2.12	2.75	0.037	7.11
2011	0.59	6.03	0.81	1.33	3.20	10.08	0.25	2.77	0.00	4.84	2.80	2.23	3.10	0.036	6.06
2012	0.67	6.68	0.58	1.48	3.38	10.19	0.25	2.84	1.67	5.03	3.10	2.16	2.35	0.055	6.87
2013	0.72	6.53	0.86	1.54	3.44	9.61	0.19	2.93	2.64	5.38	3.11	1.62	3.54	0.027	6.85
2014	0.63	6.63	0.70	1.76	3.65	12.12	0.21	3.01	3.23	5.94	3.01	1.62	2.94	0.037	7.98
2015	0.63	6.47	0.94	2.03	3.57	11.68	0.21	3.03	1.89	6.36	3.18	1.48	3.07	0.037	6.20
2016	0.65	6.35	0.53	1.99	3.65	13.07	0.26	3.15	3.30	6.66	2.83	1.48	3.28	0.026	4.95
2017	0.64	6.78	0.85	2.16	3.94	13.13	0.26	3.24	2.52	7.48	2.79	1.60	3.40	0.046	9.50
2018	0.78	5.04	0.88	2.18	4.33	13.53	0.27	3.31	3.59	7.21	3.24	1.91	3.63	0.045	7.64
2019	0.79	6.33	0.62	2.33	4.87	13.88	0.28	3.39	2.82	7.14	3.16	1.95	3.71	0.025	6.97
2020	0.70	6.52	0.50	2.41	5.12	13.97	0.27	3.58	2.72	7.44	3.40	1.96	3.90	0.048	8.80
2021	0.61	6.67	0.84	2.42	5.27	14.59	0.27	3.77	2.53	7.71	3.17	2.09	3.97	0.051	9.39
2022	0.70	6.45	0.51	2.36	5.42	14.62	0.28	3.96	3.09	7.31	3.03	2.17	4.18	0.058	8.90
Average	**0.66**	**6.33**	**0.73**	**1.95**	**4.08**	**12.42**	**0.25**	**3.20**	**2.31**	**6.38**	**3.06**	**1.87**	**3.37**	**0.041**	**7.48**
	1%	**8%**	**1%**	**2%**	**5%**	**15%**	**0%**	**4%**	**3%**	**8%**	**4%**	**2%**	**4%**	**0%**	**9%**

Table 19: Biomethanol Potentials by countries (regions)

Year	Bioethanol (Million Tonnes Oil Equivalent, Mtoe)														
	Northern Africa			**Western Africa**			**Central/Northeastern Africa**			**Eastern/ Southeast Africa**			**Southern Africa**		
	Algeria	**Egypt**	**Morocco**	**Ivory Coast**	**Ghana**	**Nigeria**	**CAR**	**DRC**	**Sudan**	**Ethiopia**	**Kenya**	**Mozambique**	**Angola**	**Namibia**	**South Africa**
2010	0.32	3.32	0.49	0.77	1.84	6.51	0.15	2.70	0.00	2.47	1.65	1.19	1.63	0.020	3.74
2011	0.35	3.48	0.48	0.77	1.83	5.86	0.15	2.82	0.00	2.71	1.55	1.25	1.83	0.020	3.22
2012	0.40	3.83	0.35	0.88	1.93	5.95	0.15	2.89	1.11	2.81	1.72	1.20	1.42	0.030	3.62
2013	0.43	3.72	0.52	0.92	1.97	5.53	0.11	2.99	1.76	3.01	1.75	0.92	2.09	0.015	3.63
2014	0.37	3.77	0.43	1.06	2.09	7.00	0.12	3.08	2.14	3.32	1.68	0.92	1.72	0.020	4.21
2015	0.38	3.66	0.57	1.20	2.05	6.81	0.12	3.09	1.25	3.56	1.77	0.83	1.78	0.020	3.30
2016	0.39	3.60	0.32	1.17	2.09	7.69	0.15	3.22	2.18	3.71	1.58	0.83	1.90	0.014	2.64
2017	0.38	3.83	0.52	1.28	2.25	7.71	0.15	3.31	1.68	4.14	1.56	0.91	1.96	0.025	4.99
2018	0.46	2.91	0.54	1.30	2.48	7.91	0.16	3.38	2.41	4.01	1.80	1.09	2.09	0.025	4.08
2019	0.47	3.60	0.38	1.38	2.78	8.01	0.16	3.46	1.93	3.99	1.77	1.11	2.13	0.013	3.71
2020	0.41	3.71	0.31	1.43	2.92	8.07	0.15	3.66	1.86	4.16	1.92	1.11	2.24	0.027	4.65
2021	0.36	3.79	0.52	1.44	3.00	8.40	0.16	3.85	1.72	4.28	1.81	1.18	2.28	0.028	4.97
2022	0.41	3.66	0.31	1.36	3.09	8.36	0.16	4.04	2.06	4.05	1.75	1.21	2.40	0.031	4.68
Average	**0.39**	**3.61**	**0.44**	**1.15**	**2.33**	**7.22**	**0.14**	**3.27**	**1.55**	**3.56**	**1.72**	**1.06**	**1.96**	**0.022**	**3.96**
	0.63%	**5.76%**	**0.70%**	**1.84%**	**3.73%**	**11.53%**	**0.23%**	**5.22%**	**2.47%**	**5.68%**	**2.74%**	**1.69%**	**3.13%**	**0.04%**	**6.32%**

CHAPTER FIVE

CHARACTERIZATION OF WOOD, LEAVES, BARKS, AND POD WASTES FROM *PROSOPIS AFRICANA* BIOMASS FOR BIOFUEL PRODUCTION

5.1 Introduction

The International Energy Agency (IEA) projects that global energy consumption will drop by ~ 8% by 2050, with renewable sources such as biomass, wind, hydro, solar, and geothermal accounting for about 90% of that energy. In the face of climate change, transitioning from fossil fuels to clean energy sources like biomass is important to maintain an eco-friendly environment [198]. Following the business-as-usual of fossil fuel exploration, production, and consumption that add GHGs, especially carbon dioxide (CO_2) to the atmosphere, causing climate change, there is a need to identify and develop more potential biomass feedstocks from our environment [199], [200]. The damage caused to the environment due to fossil fuel consumption and the corresponding emission of GHGs has led to an interest in energy transitions to renewables like biomass, wind, solar, hydro, geothermal, and gravitational energies [201]. The Intergovernmental Panel on Climate Change (IPCC) has estimated that to limit the average global warming to 1.5 °C, biomass energy utilization coupled with carbon capture and sequestration has a two-third chance of removing 12 Giga tonnes of CO_2 annually. This amounts to 25 % of the current emissions and would require 25 % to 80 % of the global agricultural land amounting to 0.4 and 1.2 billion hectares of land [7], [8]. Biomass, as a sustainable energy source, can be planted, converted to energy, and replanted. During growth, they naturally sequester CO_2 from the atmosphere through photosynthesis. These grown plant biomass materials can be collected and valorized for useful biofuels products (Tan R, *et al*., 2020) [203]. Its valorization to energy is one of the most environmentally beneficial solutions to mitigate greenhouse gases (GHGs) emissions without disrupting food security and at the same time preserving land use [204]. Historically, this biomass has been traditionally burned for cooking and heating, resulting in significant drawbacks [205].

Many underutilized biomass materials have not yet been explored and studied, and one such not well-studied lignocellulosic biomass is *Prosopis africana* biomass. It is a flowering plant species (Genus: *Prosopis*) and is often used as a food flavor in Nigeria, Benin, Cameroun, Burkina Faso, Togo, and other African countries. When compared to other sources of biofuel feedstocks, these feedstocks exhibit superior biomass output, as well as resistance to frost/heat/drought tolerance, irrigation response, and pod production. The tree can achieve an annual growth rate of 5 – 7 cm in diameter and 2 – 4 cm in height per year. In greenhouse studies, they demonstrated their ability to grow on a nitrogen-free media. The estimated cost for the harvested PA was $1.50 per million BTUs, which is favorable in comparison to biomass feedstock (Felker, *et al.*, 1981). Furthermore, PA biomass is differentiated from other biofuel feedstocks by its renewable sources, production processes, biodegradability, diverse applications, lower environmental impact, market demand, production costs, and unique material properties. These factors contribute to the distinct role of PA in the landscape of sustainable materials and biofuels, adhering to the circular economy through improved resource utilization and waste management [207]. Integrating bioenergy systems with other areas of the circular economy, such as waste management and sustainable agriculture, is critical (Leela, *et al*, 2024), and will help in climate change mitigation and advancing clean energy solutions

The chemical composition of the lignocellulosic biomass—cellulose, hemicellulose, and lignin [209] determines its suitability for bioenergy. Agricultural residues like wheat straw and sugar cane bagasse are preferred due to their low lignin content (< 20 wt. %) and higher cellulosic and hemicellulose content. Preparing and analyzing biomass materials, such as agricultural residues or non-food crops, to make them suitable for biofuel production entails pretreatment processes of the biomass to enhance its accessibility for conversion, and subsequently characterizing its properties to optimize the biofuel production process. This is to improve efficiency, sustainability, and yield in the production of biofuels from renewable biomass sources. The pretreatment process contains the drying, grinding, and sieving of feedstocks. The conversion process includes feeding, conversion, separation of intermediate products, collection and upgrading, and collection of products. Several types exist, such as thermochemical (combustion, pyrolysis, gasification), biochemical (fermentation, anaerobic digestion), mechanical (size reduction, pelletization), chemical conversion (hydrolysis, chemical treatment); electrochemical (microbial fuel cell), direct combustion [198], [205].

This characterization is important as the PA woods, leaves, barks, and pods are not edible and are always discarded as waste. These PA biomasses do not have any known bioenergy application. In this regard, the originality of the study is to understand the biofuel potential that can be obtained from the pulverized PA pod wastes after the seed extractions, as well as the wastes from the barks, wood, and leaves through physical, chemical, and thermal characterizations. The motivation is to stimulate interest among the scientific community, sustainability enthusiasts, industrialists, and policymakers to consider scaling up PA as feedstocks for biofuel production. Therefore, comprehensive characterization of these samples is required for efficient bioenergy conversion. To the authors' knowledge, such information is notably lacking in existing literature, underscoring the need for further investigation and documentation. This study provides an in-depth analysis of *Prosopis africana* biomass as a biofuel feedstock, focusing on the underutilized parts such as pods, bark, wood, and leaves.

The primary objective is to comprehensively analyze their physical, chemical, and thermal properties for biofuel applications. The data generated will be used in developing efficient processing techniques and informed policymaking toward circular economy to promote biomass waste utilization for biofuel production. Specifically, the study adheres to standardized procedures to characterize the PA woods, barks, leaves, and pods biomass towards biofuel production and providing useful data for scaling up and inclusion into the bioenergy crop database. The characterization parameters determined were the moisture content, volatile content, ash content, fixed carbon content, total solid content, carbon, hydrogen, nitrogen, sulfur, oxygen compositions, lignin, cellulose, and hemicellulose content. These were used to assess the suitability of PA wastes for biofuel production. This study focused on *Prosopis africana* primarily cultivated in North Central Nigeria. This highlights the necessity to also investigate those grown in other countries across sub-Saharan Africa.

5.2 Materials and Methods

5.2.1 Field sampling and sample preparation

Prosopis africana trees (**Fig. 14**) are grown in Argentina, Kenya, Nigeria, Benin, Cameroun, Burkina Faso, and other African countries (Ángela-Mariela, *et al*,, 2021).

Fig. 14: *Prosopis africana* Tree

The wood, leaves, bark, and pod wastes from *Prosopis africana biomass* were collected from a mixed-aged tree stand located at the campus of the African University of Science and Technology (AUST), Abuja, Nigeria. The site coordinates are Latitude. 9.00046 ° and Longitude. 7.42149 ° with an average annual temperature of 26 °C and annual precipitation of ~1389 mm. The following samples were collected, wood from branches with varying diameters collected from the ground; bark was separated from the stem of the trees in the lower part of the stem below breast height using a knife; green leaves taken from different branches in the lower canopy, and pod shells were obtained from pods that were collected from the ground and opened for seed release.

The samples were air-dried at ambient temperature for 51 days. The samples were first crushed into coarse particles using a milling jaw crusher (BB 50 model), pulverized further with a Binatone grinder (Model BLG-402, 350 W, China), and then sieved (Endecotts Lab Test Sieve; ISO 3310-1) through a 1 mm, 425 µm, 150 µm mesh screen. The 1 mm and 425 µm particles had to be ball milled (with Planetary Mill, Model PMV1-2L, and SN/MSE200709001) to obtain adequate materials at 150 µm which were then used for the characterization. The samples were labeled S1 for the woods, S2 for the leaves, S3 for the bark, and S4 for the pods as shown in **Fig 15**.

Fig. 15: Samples of the Prosopis Africana's (a) wood, (b) Leaves, (c) barks, and (d) pods.

Three replicates were analyzed for each biomass material sample. The process for assessing the PA biofuel potential of the various components of the PA biomass is illustrated in **Fig. 16**.

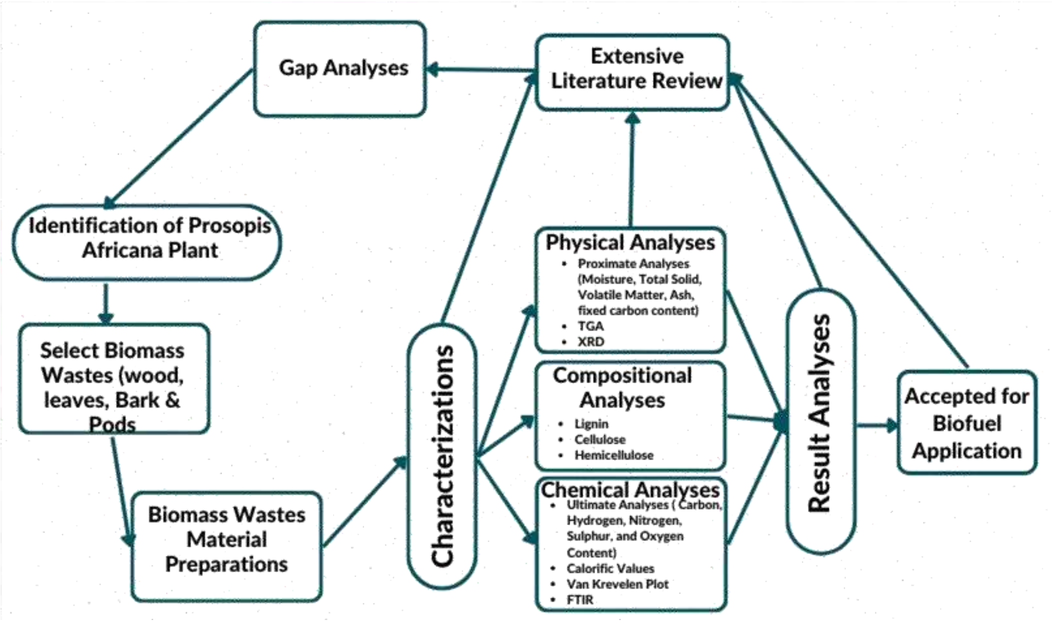

Fig. 16: Steps in the valorization of the *Prosopis africana* PA biomass from its wood, bark, leaves, and pods for biofuel application

5.2.2 Materials Characterization

Morphological Analyses**:** The physical structure change of PA biomass was observed by utilizing a scanning electron microscope (SEM) model Phenom ProX (PhenomWorld, Eindhoven, Netherlands). Particles of the samples (S1, S2, S3, and S4) were placed on double adhesive carbon tape placed on a sample stub and coated with 5 nm of gold to prevent surface charging. The sputter coater model Q150R is made by Quorum Technologies. The samples were placed in the chamber of the SEM machine, viewed through NaVCaM, and transferred to SEM mode. Energy dispersive X-ray (EDAX, USA) was used for the quantitative elemental analysis of the samples. The bulk densities were determined by adding 20 g of the samples of pulverized PA wood, leaves, bark, and pod in a graduated cylinder calibrated in milliliters (ml). These samples were agitated for 2 min. to close up the porosity and compact the particles [71].

***Proximate Analyses*:** The American Society for Testing Materials (ASTM) standards were used for the proximate analyses, moisture content, volatile matter content, ash content fixed carbon content, and the calorific value of the biomass waste samples.

Moisture Content (MC): ASTM E871 – 82 was used to determine the MC [212]. The weight of the dry silica crucible ws weighed as α. 1 g of each of the samples was weighed in the silica crucible without a lid as β, and heated in an electric hot air oven for 2 hours at 105 °C – 110 °C. After which the crucible is taken out, cooled in a desiccator, and weighed for weight loss γ. The total solid was then calculated with **Eq. 1** and MC with **Eq. 2**.

$$Total\ Solid\ (TS\%) = \left(\frac{\beta - \alpha}{\gamma}\right) * 100 \tag{1}$$

$$Moisture\ Content\ (\%M) = 100 - TS(\%) = \left[1 - \left(\frac{\beta - \alpha}{\gamma}\right)\right] * 100 \tag{2}$$

Volatile Matter Content (VMC): ASTM Standard E-872 -82 [213] was used to determine the VMC. 2 g of the pulverized samples were placed in crucibles and covered with lids before being incinerated in a muffle furnace at a temperature of 850 °C for 7 min, and then allowed to cool in a desiccator. The loss in weight at 850 °C of the biomass sample accounts for the VMC as shown in **Eq. 3**.

$$Volatile\ Matter\ Content\ (\%\ VMC) = \left(\frac{\varphi_1 - \varphi_2}{\varphi_1}\right) * 100 \tag{3}$$

Where ϕ_1 and ϕ_2 are the weights of the PA samples before and after heating respectively.

Ash Contents: ASTM Standard E1755-01 (ASTM-E1755–01, 2020) was used to determine the Ash content. 2 g of the samples (ϕ_1) were put into pre-weighed crucibles before incinerating at a temperature of 730 °C for 5 h in an electric muffle furnace without the crucible lids ($\propto_1$). This was to ensure complete combustion. The crucible is then taken out, cooled first in the air then in a desiccator, and weighed ($\propto_2$). The weight of residue (inorganic matter) left in the crucible was used for the ash content was calculated as in **Eq. 4**

$$Ash\ Content\ (\%\ Ash) = \left(\frac{\propto_1 - \propto_2}{\varphi_1}\right) \qquad (4)$$

Fixed Carbon Content (FCC): The percentage of the FCC was determined as Initial biomass less of the sum of % MC, % VMC, and % Ash [214] shown in **Eq. 5.**

$$Fixed\ Carbon\ Content\ (\%\ FCC) = 100 - (\%\ M + \%\ VMC + \%\ Ash\ ) \qquad (5)$$

***Ultimate Analyses*:** The ultimate analyses for CHNS/O were conducted on the PA biomass by placing 2 g each of the S1, S2, S3, and S4 to determine the carbon, nitrogen, oxygen, hydrogen, and sulfur. The CHN was determined using the LECO CHN-2000 analyzer while the LECO S-144DR analyzer was used for the sulfur content determination by the ASTMD4239−11 standard. The oxygen content was therefore determined using **Eq. 6**

$$\%\ O = 100 - (\ \%\ C + \%\ H + \%\ N + \%\ S + Ash) \qquad (6)$$

***Bio-Chemical (Compositional) Analyses*:** In this analysis, the percentages of lignin, cellulose, and hemicellulose were determined. Bleaching is one of the two major procedures for effective cellulose extraction procedures from lignocellulose biomass [215]. To separate and determine the cellulose, the acid bleach method was applied, where 2 g of the various samples of samples were filled with water and ethanol in the SOXHLET apparatus and allowed for 7 h to de-wax them. They were afterward bleached with 1.5 % sodium chlorite ($NaClO_2$) for 2 h at a 3.5 pH level and temperature of 70 ^oC. This process was repeated until white-colored and pure cellulose was obtained, filtered, dried, and weighed. For the hemicellulose determination, the filtrates from above were treated with 1 M of sodium hydroxide (NaOH) at 65 ^oC for 2 h and then titrated with 6 M of Hydrogen Chloride (HCl) at a pH level of 5.5.

The resulting products were precipitated with pellets of ice-cold ethanol. These were washed with distilled water to remove excess NaOH before centrifuging to obtain pure hemicellulose, and subsequently dried in a hot air oven for 24 h and then weighed. Lignin content determination was carried out by the acid hydrolysis method. One gram of the sample's powder was hydrolyzed with 72 % sulphuric acid (H_2SO_4) and placed in an oven for 2 h at 121 °C after which it was separated by filtration into acid-soluble lignin (filtrate) and acid-insoluble lignin (residue). The former was then determined with the use of a UV-visible spectrophotometer.

$$Acid\ Soluble\ Iignin\ (\%) = \left(\frac{D_{sample} * UV_{abs} * V_{filtrate}}{\varepsilon * Wt_{ODW} * L_p}\right) * 100 \qquad (7)$$

where,

$$D_{sample} = \left(1 - \frac{V_{solvent}}{V_{sample}}\right) \qquad (8)$$

where D_{sample} is the dimensionless dilution, UV_{abs} = the average absorbance for the sample, $V_{filtrate}$ = filtrate volume, L_P = UV path length (cm), Wt_{ODW} = Oven dry weight of the sample (mg), Ɛ = absorptivity, V_{sample} = sample volume of the GA fruit powder, and $V_{solvent}$ is the Volume of the diluting solvent.

The determination of the ether extractives of the PA biomass was carried out using the Randall method [216], in which a SOXHLET apparatus was used by adding 2 g of PA wood, leaf, bark, and wood samples in the sample chamber and 250 ml of ether was also placed in the receiver flask and then placed on a heating mantle for 7 h at 80 ^{o}C to allow for extraction. The extract was then dried in the oven at 70 ^{o}C until a constant weight was attained. Consequently, the extractives were calculated [71].

***Fourier-Transform Infrared Spectroscopy (FTIR*)**: The functional groups in the PA biomass were characterized by FT-IR spectroscopy (Thermo Fisher Scientific, USA) to measure the samples' absorption or transmission of infrared radiation. The samples were placed in a sample holder, after mixed with KBr in the ratio of 1:10 and compressed with a press at 15 psi to obtain pellets. First, the background measurements were taken by measuring the infrared radiation passing through an empty sample holder to correct for any infrared radiation absorbed or scattered by the sample holder or the instrument itself. All the spectra were recorded in the absorbance mode at the wavenumber range of 4000 – 400 cm^{-1} (mid-infrared region). This process produces a spectrum that represents the unique absorption pattern of the samples.

***X-ray diffraction (XRD) analyses*:** XRD characterization of thin film samples was done with an X-ray Diffractometer (Thermo scientific model: ARL'XTRA X-ray and serial number 197492086, Switzerland). The X-ray tube machine was allowed to warm up for one hour before it was used for analysis while the settings were done in the computer system. As the X-rays were generated in a cathode ray tube, the thin film samples were placed on the sample holder and inserted into the Analyzer. The intensity of diffracted X-rays was continuously recorded as the samples and detectors rotated through their respective angles. These were carried out with Cu-Kα radiation of wavelengths 1.540598 Å generated at 40 mA and 45 kV (Empyrean). The Ruland–Vonk method was used to estimate the crystallinity index (CrI) of the samples as shown in **Eq. 9**.

$$\text{Crystallinity Index } (CrI) = \left(\frac{Crystaline\ peak\ Areas}{Total\ Peak\ Areas\ (crystalline + amorphous)}\right) \qquad (9)$$

***Thermogravimetric Analysis (TGA*):** The thermal behaviors were characterized using thermogravimetric analysis (TGA; PerkinElmer 4000, USA), and the MSE-TGA procedure were followed, covering precautions, step-by-step instructions, and necessary precautions for successful thermogravimetric analysis, ensuring the samples, S1, S2, S3, and S4 were compatible with platinum crucible at planned temperatures range of 20 – 1200 °C (10 °C/min) and in a nitrogen atmosphere.

The calorific value quantifies the heat release per unit of biomass during combustion. The higher heating value (HHV), usually influenced by the elemental composition, moisture, and ash content, reflects the gross calorific value (GCV). An elevated HHV underscores the significant potential of the samples (S1, S2, S3, and S3) as a bioenergy source. Calculations of HHV and Lower Heating Value (LHV) were determined using the method [217] in **Eq. 10** and **Eq. 11**.

$$HHV\left(\frac{MJ}{kg}\right) = 1.192\,(\%\,H) + 0.3443\,(\%\,C) - 0.024\,(\%N\,) - 0.113\,(\%\ O_2) + 0.093\,(\%\,S) \tag{10}$$

$$LHV = HHV - 0.212\,(\%\,Hydrogen) - 0.0245\,(\%\,Moisture) - 0.008\,(\%\,Oxygen) \tag{11}$$

Atomic Ratios (H/C and O/C), Van Krevelen Plot and Biofuel Reactivity

The H/C and O/C atomic ratios were calculated [218] as follows using the Eq. 12 and Eq. 13.

$$\boldsymbol{H}\!:\!\boldsymbol{C\ ratio} = \frac{\%\ \text{Hydrogen Content}}{\%\ \text{Carbon Content}} \tag{12}$$

$$\boldsymbol{O}\!:\!\boldsymbol{C\ ratio} = \frac{\%\ \text{Oxygen Content}}{\%\ \text{Carbon Content}} \tag{13}$$

The biofuel's reactivity was assessed through elemental and proximate analyses. This involved calculating the ratio of volatile matter to fixed carbon content, as well as molar ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C) in the samples.

5.3 Results and Discussions

The bioenergy potential of *Prosopis africana* (PA) wastes—wood, leaves, bark, and pods—is evaluated and discussed in this section, focusing on their morphology, chemical composition, and thermal energy properties.

5.3.1 Morphology

The morphology of the samples of PA biomass was studied to understand the surface characteristics (texture, pore, and pore size) that influence the performance and the behavior of biomass. **Fig. 17 (a – d**) shows the respective microscopic structure of the samples revealing the unique surface patterns, sizes, and shapes of the samples. The internal structures are porous, suggesting they can effectively release volatiles and can be chemically treated for energy applications [219]. The bulk densities of wood, leaves, bark, and pod waste were 0.363 g/cm^3, 0.361 g/cm^3, 0.507 g/cm^3, and 0.435 g/cm^3 respectively, indicating the wood and leaves have larger granular particles that created inter-particle voids, leading to the lower value obtained than the bark and pods. The densities of the feedstocks have been reported to significantly influence their behaviors during the thermochemical/biological conversion processes [220], [221]. The EDS analysis of the PA biomass showed Carbon, Nitrogen, Calcium, and Aluminum in high concentrations as shown in **Table 20.** The suitability of biomass for energy generation through combustion depends on its low metallic element content. Alkali metals like calcium and potassium, identified through EDS analysis, can adversely impact thermochemical conversion processes in biofuel production, leading to undesirable by-products. The calcium is more in the wood and the pods. It is noteworthy that potassium might act as a catalyst, potentially enhancing the biomass conversion rate (Qianqian Guo, *et al.*, 2023).

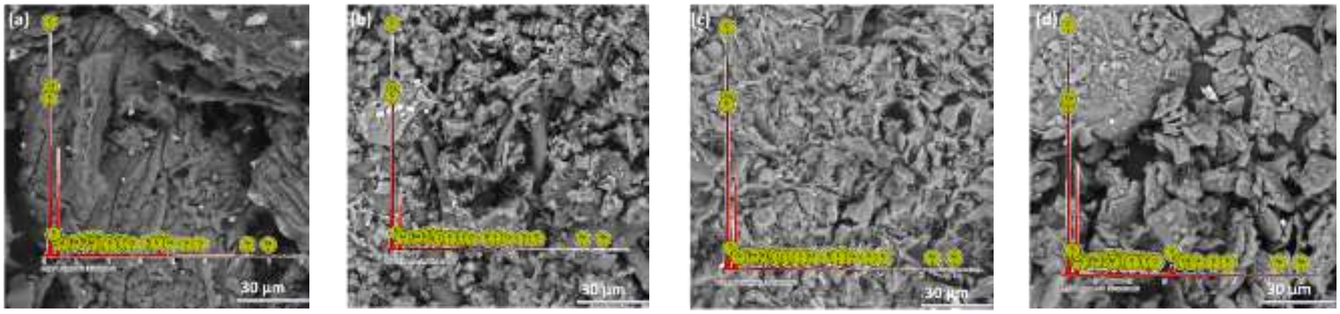

Fig. 17: Scanning Electron Micrograph (SEM) of the samples and EDS of wood (a), leaves (b), barks (c), and pods (d))

Table 20: Elemental composition of PA plant by EDS

			Wood (S1)		**Leaves (S2)**		**Barks (S3)**		**Pods (S4)**	
Element Number	**Element Symbol**	**Element Name**	**Atomic Conc.**	**Weight Conc.**	**Atomic Conc.**	**Weight Conc.**	**Atomic Conc.**	**Weight Conc.**	**Atomic Conc.**	**Weight Conc.**
6	C	Carbon	84.81	79.4	88.42	84.63	86.21	82.22	84.3	78.91
7	N	Nitrogen	12.32	13.45	9.7	10.83	12.06	13.42	13.04	14.23
20	Ca	Calcium	0.59	1.84	0.39	0.84	0.36	1.14	0.98	2.99
13	Al	Aluminum	0.51	1.08	0.32	0.71	0.31	0.65	0.38	0.8
14	Si	Silicon	0.45	0.98	0.27	0.52	0.15	0.42	0.34	0.74
12	Mg	Magnesium	0.32	0.61	0.13	0.42	0.17	0.38	0.24	0.6
19	K	Potassium	0.16	0.5	0.21	0.38	0.2	0.37	0.17	0.4
16	S	Sulfur	0.19	0.47	0.14	0.36	0.11	0.33	0.09	0.4
26	Fe	Iron	0.1	0.45	0.13	0.32	0.17	0.32	0.19	0.37
15	P	Phosphorus	0.17	0.42	0.06	0.29	0.12	0.29	0.19	0.35
11	Na	Sodium	0.23	0.41	0.09	0.27	0.1	0.25	0.08	0.23
17	Cl	Chlorine	0.14	0.39	0.1	0.27	0.05	0.21	0	0
22	Ti	Titanium	0	0	0.04	0.15	0	0	0	0

5.3.2 Proximate and Ultimate Analyses

The proximate results of the samples are presented in **Table 21** along with another biomass. It shows that the moisture contents (MC) of the PA biomass samples ranged between 3 % and 8 %, significantly below the recommended range of 10 - 12 % by O NORM M7135 [223] and this makes the PA biomass suitable feedstock for combustion, gasification, and pyrolysis [224]. The volatile matter was more in S2 and S4 (**Fig 18a**), while the carbon content was relatively the same for S1, S3, and S4 (**Fig 18b**). For biofuel combustion, low MC is desirable, while high MC poses a challenge during burning. As shown in Fig 6a, they also exhibited high volatile matter contents of 71.43 %, 74.34 %, 62.10 %, and 75.82 % for the PA wood, leaves, barks, and pods respectively, implying good potential for generating gaseous fuel. It can be observed that the volatile matter of the PA biomass is relatively close to those of another biomass shown in **Table 21**. The higher volatile matter content due to its organic nature is associated with increased liquid yield, suggesting the potential for significant condensable and non-condensable [225] vapor generation during utilization. However, excessive volatile matter can degrade combustion performance, requiring larger quantities of high-pressure secondary air for efficient combustion and leading to undesirable outcomes such as dark smoke emission, heat loss, and environmental pollution [218]. Carbonaceous materials (fixed carbons) were obtained after the biomass samples were de-volatilized. In this study, the PA pods have the lowest FC (13.12 %) when compared to that of wood, bark, and leaves, and the effect of this was seen in its calorific value. Ash contents of the various samples were also found to be less (1.67 – 4.04 %). The result also reveals that the PA biomass has favorable characteristics for combustion or pyrolysis due to its lower ash content and higher volatile matter. A lower ash content is advantageous for efficient burning, as higher ash content can act as a heat sink and reduce combustion’s system efficiency. Furthermore, the fixed carbon composition falls within a satisfactory range when compared to other biomass sources. In summary, all the samples demonstrated low Ash, MC, high FC, and high VMC, thereby inferring suitability for biofuel production.

The ultimate analyses result showing the CHNS content are presented in **Table 21**, showing the biomass fuel efficiency and possible pollutant characteristics. These are compared with those of another biomass. These biomass samples exhibit carbon content ranging from 44.60 % to 51.01 %, comparable to values reported for other biomass materials in **Table 21**. Literature values support a direct correlation between carbon percentage and heating value, indicating that higher carbon content results in elevated fuel heating values [226]. The carbon contents are relatively close in the wood, bark, and pod, as well as higher when compared to that of the PA leaves at 44.65 %.

The heating value of biomass is usually affected by the oxygen content of the samples which is a major setback of biomass in comparison with coals. From this work, the oxygen content of PA woods is 57.57 %, which explains the reason for the low HHV of 17.75 MJ/kg and an LHV of 15.98 MJ/kg (**Table 21**). In addition, the bark exhibited lower oxygen (41.11 %) with a higher heating value of 20.49 MJ/kg as shown in **Table 21**. Oxygen content is an important fuel quality that determines the behavior of their combustion [218]. Nitrogen and sulfur percentages are relatively low (**Table 21**), suggesting minimal generation of SO_x and NO_x gases during pyrolysis. Furthermore, the lower sulfur content in the PA biomass is beneficial for reducing corrosion problems, contributing to an extended lifetime for boilers and pipes. In this study, the Sulphur contents of the PA samples are significantly < 1 % and relatively lower than other biomass, and this low S content depicts choice candidates for biofuel production.

Table 21: Proximate and ultimate analysis in comparison with other lignocellulosic biomass feedstocks

Biomass/Residues		**Proximate Analyses (wt. %)**				**Ultimate Analyses (wt. %)**					**Reference(s)**
		MC	**VMC**	**AC**	**FC***	**C**	**N**	**H**	**S**	**O***	
Wood	PA wood	3.13	71.43	3.86	21.58	49.23	0.52	6.13	0.15	57.57	**This study**
	Sesbania Wood	7.72	82.62	1.13	16.25	43.97	0.44	4.85	<0.30	47.72	[217]
	Rubberwood sawdust	5.38	77.47	2.01	17.50	48.49	0.18	7.15	0.03	41.99	[227]
Grasses/Leaves	PA Leaves	4.42	74.34	1.64	19.60	44.65	2.27	4.49	0.22	48.37	**This study**
	Sesbania Leaves	8.63	76.13	13.92	9.95	41.03	3.72	5.99	<0.30	35.04	[217]
	Corn Leaf	1.20	73.4	9.70	15.70	47.70	2.90	6.40	0.90	42.10	[228]
	Maple Leaf Wastes	6.28	81.2	6.12	6.4	49.4	1.98	4.32	0.16	44.14	[229]
	Sugar Bagasse	8.12	69.82	6.57	15.49	39.8	0.50	5.94	0.19	53.57	[230]
Field Based	PA Barks	7.28	62.10	1.74	28.88	51.01	1.12	6.34	0.42	41.11	**This study**
	Sesbania Barks	8.27	73.55	8.52	17.93	43.97	1.95	5.59	<0.30	37.64	[217]
Processed-based	PA Pods	7.02	75.82	4.04	13.12	49.87	2.56	5.33	0.13	42.11	**This study**
	Peanut Shells	5.16	80.24	6.12	8.48	46.86	1.03	6.84	0.29	44.98	[231]
	Prosopis juliflora Pods	7.90	87.67	0.21	4.23	41.77	3.59	6.55	26.30	21.8	[214]
	Cocoa Pods	11.07	61.73	16.24	10.96	48.7	1.19	0.75	0.97	48.39	[232]
	Mesquite Pod	3.93	78.7	9.01	12.29	43.29	4.62	5.59	0.21	43.09	[233]

(*) Calculated by the current author

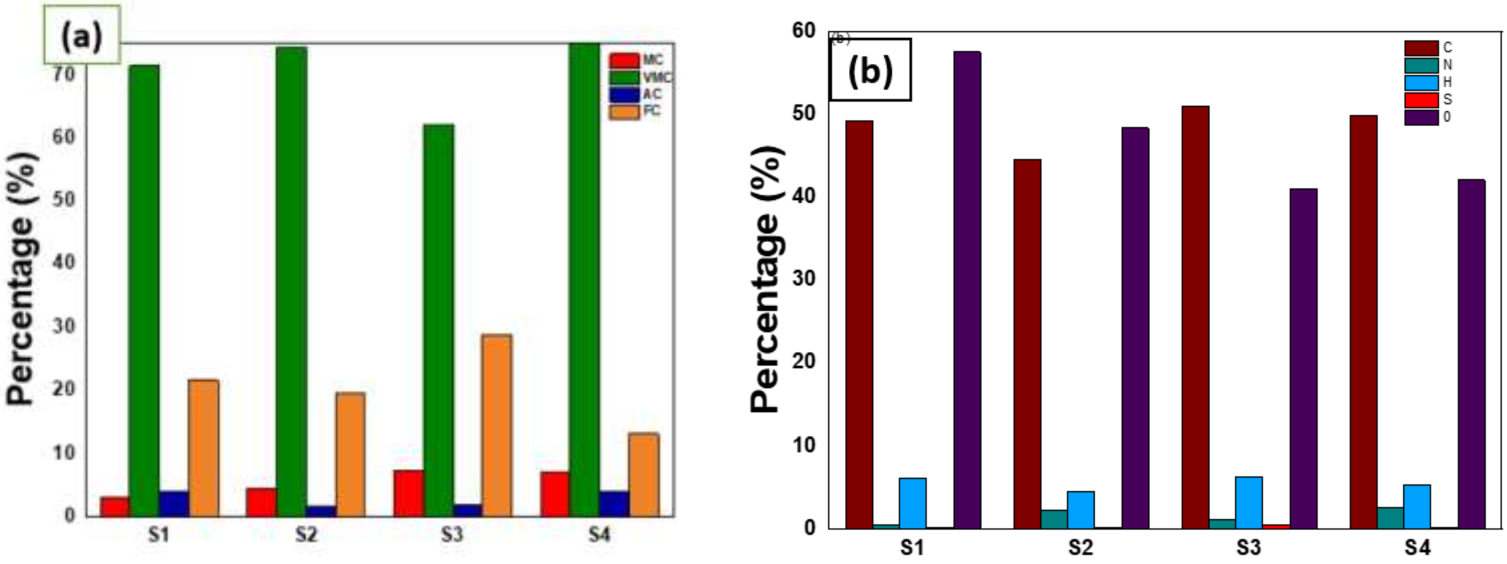

Fig. 18: (a) Proximate Analyses and (b) Ultimate (CHNS/O) Analyses

5.3.3 Bio-Chemical (Compositional) Analyses

The contents of the main components in hemicellulose, cellulose, and lignin obtained from the samples are shown in **Table 22**. As shown, the cellulose, hemicellulose, and lignin content for the wood were 32.59 %, 10.35 %, and 55.03 % respectively, which indicate a low amount of hemicellulose and high amount of lignin. The leaves showed 34.39 % cellulose, 13.44 % hemicellulose, and 24.89 % lignin, also revealing low hemicellulose content. For the bark and pod, the hemicellulose contents were high when compared to their respective contents as shown in **Table 22**. The cellulose/hemicellulose ratio of the wood (3.15), and leaves (2.56) showed relatively high values when compared to other biomass found in the literature as shown in **Table 22**. The cellulose/hemicellulose ratios of the bark (0.83) and pod (0.61) were low due to the high hemicellulose content. These ratios are critical for ethanol yield estimation, because, feedstocks with high cellulose/hemicellulose ratios yield high ethanol [71]**.** Therefore, ethanol production from the bark and the pods will require pretreatment and additional enzymes for hydrolysis.

Table 22: Biofuel Reactivity comparison with other biomass feedstocks

		Lignocellulose Composition					Ref.(s)
Biomass/Residues		**Cellulose (%)**	**Hemicellulose (%)**	**Lignin (%)**	**C: L***	**C: H***	
Wood/bark	PA wood	32.59	10.35	55.03	0.59	3.15	This study
	Pine Bark	21.90	18.30	40.70	1.69	1.47	(Díez, *et al*, 2020)
	Spruce Bark	29.70	13.90	45.10	1.38	2.14	(Díez, D., *et al*, 2020)
	Corn stover	29.20	53.50	6.20	4.71	0.55	[235]
Grasses/Leaves	PA Leaves	34.39	13.44	24.89	1.38	2.56	This study
	Tea Leaf Brewing Waste	24.93	37.20	24.42	1.02	0.67	[236]
	Arecanut Leaf Sheath	56.80	22.40	6.30	9.02	2.54	[237]
	Corn Leaf waste	32.10	18.10	11.90	2.70	1.77	[228]
	Pineapple crown leaves	13.30	354.00	26.40	0.50	0.04	[235]
Field Based	PA Bark	43.80	52.72	52.63	0.83	0.83	This study
	Prosopis juliflora bark	26.6	30.86	4.71	5.65	0.86	[214]
	Sugarcane Bagasse	49.8	30.2	12	4.15	1.65	[235]
Processed-based	PA Pods	21.75	35.61	17.14	1.27	0.61	This study
	Rice Husks	38.60	24.90	18.60	2.08	1.55	[238]
	Bean Pods	40.70	19.90	5.60	7.27	2.05	[235]
	Cassava Peels	25.80	11.60	4.29	6.01	2.22	[238]
	Yam Peels	36.80	14.70	8.64	4.26	2.50	[238]

(*) Calculated by the current author.

5.3.4 Biofuel Reactivity and Cellulose/Hemicellulose Ratio

The reactivity of the biofuel was evaluated through elemental and proximate analyses, which included determining the ratio of volatile matter to fixed carbon content, as well as molar ratios of hydrogen to carbon (H/C) and oxygen to carbon (O/C) in the samples. The H/C ratio which is the aromaticity in the biomass material and degree of condensation is directly proportional to the energy content of the material [71]. In this study, the PA bark and pod revealed the lowest O/C ratio when compared with that of the wood and leaves (**Table 23).** The Volatile Matter to Fixed Carbon (VMC/FC) ratio is higher than the atomic ratios, indicating potential for biofuel production, particularly solid biofuel. Among the different parts of Prosopis Africana, the pods exhibit the highest VMC/FC ratio.

Furthermore, the cellulose/hemicellulose ratio of biomass materials is crucial for predicting ethanol production [239], [240], [241]. The higher cellulose/hemicellulose ratios of the PA wood (3.15) and leaves (2.56) will yield more ethanol. In this study, the bark and the pod have a lower ratio due to the hemicellulose content, implying pretreatment and perhaps hydrolysis would be required before ethanol production.

Table 23: Characterization of PA woods, leaves, barks, and pod wastes

Characterizations	Properties	PA wood	PA Leaves	PA Bark	PA Pods
Morphology	Bulk Density (g/cm^3)	0.363	0.361	0.507	0.435
Proximate Analyses	Moisture Content (%)	3.13	4.42	7.28	7.02
	Volatile Matter Content (%)	71.43	74.34	62.10	75.82
	Ash Content (%)	3.86	1.64	1.74	4.04
	Fixed Carbon Content (%) *	21.58	19.60	28.88	13.12
Ultimate Analyses (dry basis)	Carbon (C) (%)	49.23	44.65	51.01	49.87
	Hydrogen (H) (%)	6.13	4.49	6.34	5.33
	Sulphur (S) (%)	0.15	0.22	0.42	0.13

	Nitrogen (N) (%)	0.52	2.27	1.12	2.56
	Oxygen (O) (%) *	57.57	48.37	41.11	42.11
Calorific Values	Higher Heating Value (HHV)*	17.75	15.23	20.49	18.72
	Lower Heating Value (LHV)*	15.98	13.83	18.79	17.19
Lignocellulose Composition	Lignin (%)	55.03	24.89	52.63	17.14
	Hemicellulose (%)	10.35	13.44	52.72	35.61
	Cellulose (%)	32.59	34.39	43.80	21.75
	Cellulose/Lignin Ratio (-) *	0.59	1.38	0.83	1.27
	Cellulose/Hemicellulose Ratio (-) *	3.15	2.56	0.83	0.61
	Ether Extractives (%)	46.91	61.73	77.52	25.50
	Protein (%)	2.58	5.66	2.59	3.01
Biofuel Reactivity	VMC/FC (-) *	3.31	3.79	2.15	5.78
	H: C (-) *	0.12	0.10	0.12	0.11
	0:C (-) *	1.17	1.08	0.81	0.84

(* Calculated by the current author)

5.3.5 X-ray Diffraction Analysis

The XRD's smoothened patterns for the PA wood, bark, leaves, and pods are presented in **Fig. 19** and offer valuable insights into the crystallinity of the biomass materials (S1, S2, S3, and S4). The diffraction patterns were obtained by scanning the 2θ values from 5° to 70°. The XRD patterns for all the samples revealed the structure and crystallinity of with two peaks in the range of 2θ values of 20.64° and 37.64° which indicates the presence of amorphous cellulose and hemicellulose. This broad peak is characteristic of the disordered regions within the cellulose fibers and the amorphous nature of hemicellulose and lignin. The reference codes 00-008-0822 for S1 and S3, 01-089-8488 for S2 and 00-055-0142 for S4. High crystallinity often correlates with resistance to chemical and enzymatic degradation due to improved molecular packing, superior barrier properties, and enhanced mechanical strength. The highly dense packing reduces the availability of sites for chemical reactions and enhances rigidity, making it more resistant to physical wear and tears, mechanical stress, and deformation thereby impacting the efficiency of biofuel production.

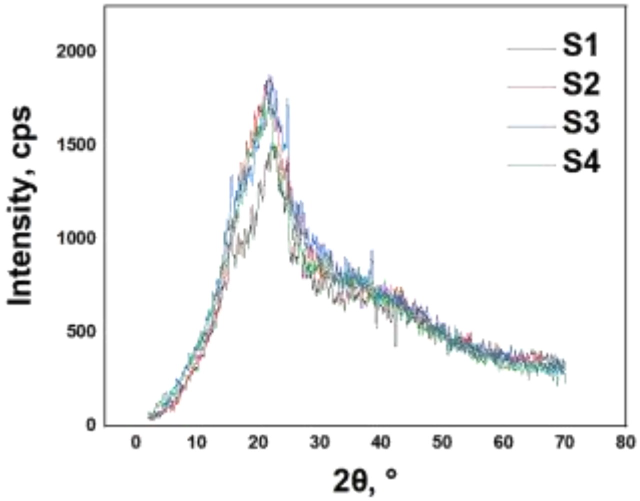

Fig. 19: Smoothened combined X-ray diffraction pattern of S1, S2, S3 and S4

5.3.6 Fourier Transform Infrared Spectroscopy (FTIR) analysis.

The obtained FTIR spectra (**Fig 20**) revealed characteristic peaks, and the functional groups present in the samples S1, S2, S3, and S4.

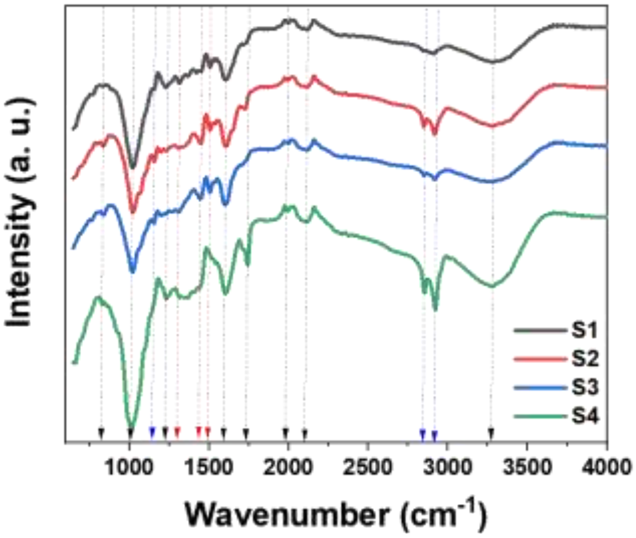

Fig. 20: Fourier transform infrared spectroscopy spectra of S1, S2, S3 and S4

The spectra showed multiple peaks and similarities in peak patterns which indicate the complex nature and the existence of similar functional groups respectively across the biomass materials. The Identification of the functional groups was based on analyses of the recorded FTIR spectra band compared with those of a reference literature. The FTIR transmittance of the PA biomass reveals the presence of –OH, –COOH, NH_2, and CO organic compound groups; Aliphatic character: 400–800 cm^{-1}, Phenols and alcoholic group: 1,000 – 1,400 cm^{-1}, Carboxyl group: 1,500 – 1,700 cm^{-1}, Hydroxyl group: 3,200–3,400 cm^{-1} [242]. They were also rich in compounds with C-C and C-H stretching or bending function groups. **Table 24** gives the results of the identified peaks and functional groups. Generally, the typical biomass components are lignin, cellulose, and hemicellulose, therefore, their typical functional groups and the infra-red signal with the possible compounds are similar as were also observed for PA biomass. The band at 3279.07 cm^{-1}, 3286.82 cm^{-1}, 3278.07 cm^{-1}, and 3003.10 cm^{-1}, for S1, S2, S3, and S4 respectively are due to the O-H stretching.

Table 24: FT-IR Spectra band assignment of the Samples

Bond	**Functional Group**	**Band Frequency (cm^{-1})**			
		S1 (Wood)	**S2 (Leaves)**	**S3 (Barks)**	**S4 (Pods)**
OH Stretching	Carboxylic acid	3279.07	3286.82	3279.07	3288.01
N-H Stretching	Amines	3382.75	3389.53	3384.54	3003.10
C-H Stretching	Alkanes	2920.16	2912.4	2912.4	2924.81
C≡C Stretching	Alkynes	2114.73	2114.73	2114.73	2114.73
C=O Stretching	Aldehyde	1741.86	1731.78	NP	1745.73
C=C Stretching	Ketones	1602.33	1603.88	1605.4	1606.2
N-O Stretching	Nitro compound	1509.3	1505.43	1505.43	NP
C-H Bending	Alkane	NP	1444.19	1448.06	NP
C-N Stretching	Aromatic amine	1307.75	1307.75	1307.75	1307.75
C-N Stretching	Amine	1230.23	1237.99	NP	1230.23
C-O Stretching	Alcohol	NP	1151.94	1155.81	NP

S=O Stretching	Aliphatic amine	1020.16	1020.16	1020.16	1020.16
C-H Stretching	Aromatics and Phenolics	834.88	834.88	834.88	834.88

*NP: No Peak

5.3.7 Thermal Analysis

The biomass's calorific value (shown in **Table 23**) serves as a crucial parameter for assessing its potential as a biofuel. In the case of PA woods, leaves, bark, and Pods, the higher heating values (HHV) are 17.75, 15.23, 20.49, and 18.72 MJ/kg respectively, while the lower heating value (LHV) stands at 15.98, 13.83, 18.79 and 17.19 MJ/kg respectively (on a dry ash-free basis). Compared to various biomass feedstocks in literature [71], the biomass materials exhibit a relatively same HHV. These values are attributed to its chemical composition, particularly the presence of extractives and lignin. Moreover, the HHV is influenced by the energy density inherent in the C–C chemical bond. The y calorific value of these PA biomass indicates their suitability for solid biofuel applications.

The TGA of the four samples is presented in **Fig. 21a,** which reveals four decomposition stages. The mass loss and derivative weight profiles are in good agreement with a report on wood-based material, which displayed the same trend of biomass degradation. The thermogravimetric analysis graph displayed three regions of mass change, while the main peaks of biomass degradation are observed from the derivative weight profile as three thermal degradation stages. The first mass loss of 9.5% occurred from room temperature to ~250°C which is attributed to the removal of volatile matter and moisture contents that are available in biomass. The moisture content from this experiment was lower than the literature values which is an indication of a positive property and high calorific value. In the second stage there is a broad and weak peak around 400°C, this is due to weight loss of 80 wt. % for samples S3 and S4. The weight loss was at 78% between 250°C and 950°C mainly for the degradation of hemicellulose, cellulose, and lignin. On the other hand, S1 and S2 experience a weight loss of 20 %. Weight loss for Sample S1 and S2 demonstrated a third stage which represents the fixed carbon level which is non-volatile matter, combustible, and oxidizable and account for 10 % loss in both samples. This occurs when the samples reach a stable state at approximately 500°C and ultimately results in a 20% weight loss, which eventually turns into ash. This stage involves the cleavage of carbon bonds in the presence of air, leading to the formation of ash. At the last region of stable weight change, ash content remains as a nonvolatile residue in oxygen after complete volatilization. Ash is an inorganic substance that is incombustible. The thermogravimetric analysis (TGA) demonstrates a consistent reduction in weight without any notable release or absorption of heat. The samples maintain their structural integrity in air atmosphere up to a temperature of 650°C, since biomass gasification consists of pyrolysis and combustion, the thermogravimetric analysis in nitrogen can represent the pyrolysis stage, and combustion thermal behavior can be observed from the thermogravimetric analysis in oxygen [71].

Fig. 21b presents the DTA curves of the thermal decomposition characteristics of the biomass elements in the selected samples S1, S2, S3, and S4. The DTA analysis revealed peaks at 385 °C for S1, 342 °C for S2, 390 °C for S3, and 399 °C for S4, demonstrating the samples' high purity. The DTA plot exhibited a three-part heat dissipation pattern, with a rapid rate of change observed between 380 and 420 °C, which is followed by a melting peak occurring at temperatures ranging from 450 to 800 °C and induced by an endothermic process. The result exhibits like patterns observed in the TGA curves. These peaks are linked to the thermal dissociation of organic constituents.

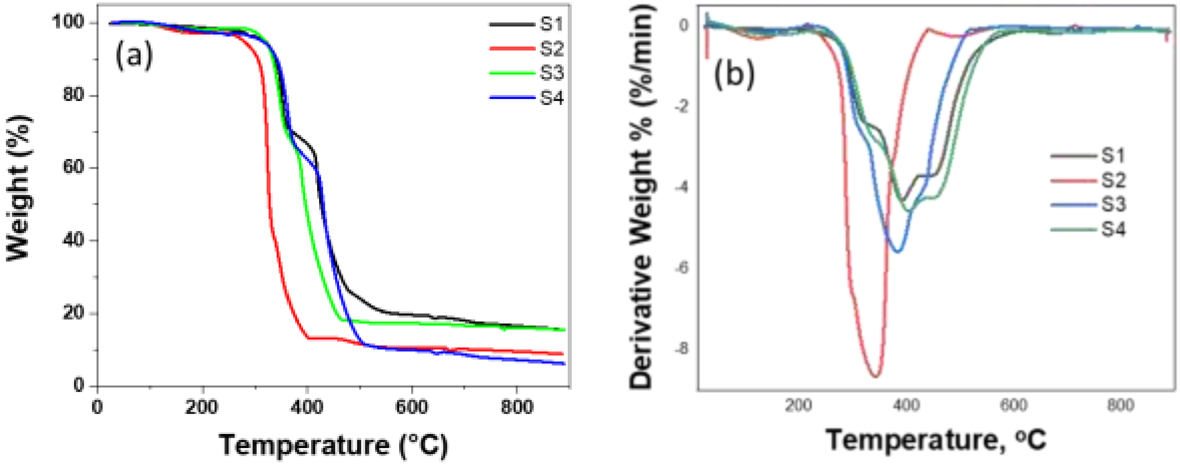

Fig. 21: Thermogravimetric Analyses; (a) TGA and (b) DTA

5.3.8 Biorefinery and Bioenergy Potential of Prosopis africana for Circular Economy

All the samples exhibit moisture and ash contents below 10 wt. %, making it suitable for direct pyrolysis, gasification, or combustion. These results indicate the samples can competently compete with other well-documented biomass feedstocks like *Prosopis juliflora* [214] and Sesbania plants [217]. However, its abundant calcium content makes it a more suitable biomaterial for diverse applications, including use as fillers in particleboard and bio-composite. The high carbon content also presents opportunities for processing into bio-charcoal and activated carbon [71].

The current demands for sustainable agriculture by the teeming population have led to the need for bio-refineries utilizing biomasses of plants, animal, and human origin. The success of bio-refineries, focusing on energy, food, and chemical production, relies on collaboration between private and public organizations. These biorefineries will aim to create a sustainable ecosystem by efficiently utilizing biomass energy stored in chemical form. This includes ensuring that the removal of evasive biomass such as the *Prosopis* species do not adversely impact the habitat of native species or disrupt local ecosystems.

Successful bio-refinery management involves considerations of biomass accessibility, soil fertility, population expansion, land availability, and agricultural outcomes. The organizational committee for sustainable biorefineries should comprise experts from various institutions, local communities, and businesses. These bio-refinery sectors include farming, bioprocessing, and wastewater monitoring, contributing to sustainable energy, manure production, and food with a socio-economic approach [243]. Utilizing PA biomass on a commercial scale, considering its potential characteristics for carbonation technology, bioethanol production, CO_2 sequestration, value additions, and ecosystem services among others [244] will contribute significantly to the global bioenergy carbon capture, utilization, and sequestrations.

5.3.9 Implications

The implications of this research are significant for increasing the contribution of biomass to the renewable energy mix in developing countries toward a circular economy. Through the assessment of underutilized biomass such as PA, the study promotes opportunities for converting biomass into bioenergy, thereby fostering greater sustainability in energy production.

The results demonstrate that the PA biomass possesses porous structures with varying degrees of crystallinity, suggesting different susceptibilities to conversion processes. Notably, the wood sample exhibited the lowest moisture content, and the pod sample had the highest volatile matter content, indicating a high potential for biofuel production. Furthermore, the higher heating values (HHV) and lower heating values (LHV) of the samples, ranging from 15.23 to 20.49 MJ/kg and 13.83 to 18.79 MJ/kg, respectively, are competitive with established lignocellulose bioenergy feedstocks. These findings position *PA* biomass as promising candidates for solid biofuel applications, highlighting their potential contribution to sustainable energy production and addressing energy security challenges in developing countries. Moreover, the comprehensive characterization of PA biomass provides valuable insights for the development of efficient biomass conversion processes and the optimization of bioenergy production systems.

5.4 Conclusions

In this study, the extensive characterization of the PA biomass was conducted to evaluate their potential application as feedstock for biofuel production. Key findings include high carbon content, low nitrogen, and low sulfur contents, establishing it as an eco-friendly solid biofuel. The low bulk densities and moisture contents of the PA biomass contribute to the cost-effectiveness of processing PA biomass into biofuel. XRD structural analysis indicated a low crystallinity index for the wastes positioning it as a promising feedstock for bioenergy refining. However, further research is essential for the pyrolysis characterization and solid (briquettes) applications, focusing on optimized particle size, hybrid composition, densification pressures, combustion properties analysis, and storage considerations. Although promising results were obtained for an informed decision to its integration as a bioenergy feedstock, further characterization research is required for its conversion routes such as pyrolysis and solid briquetting applications. In this regard, the relationship between the particle size, hybrid composition, densification pressures, and the final products are subjects for further investigation.

One of the approaches for increasing the contribution of biomass to the renewable energy mix is the valorization of biomass to bioenergy. Evaluating the potential of unconventional biomass sources could significantly accelerate the assessment for suitability as feedstock for bioenergy production as a sustainable solution. The study aimed to characterize the *Prosopis africana* biomass of wood, barks, leaves, and pods towards providing valuable data for scaling up and incorporating these materials into the bioenergy crop database. Characterizations of wood, leaves, barks, and pod wastes from *Prosopis africana* biomass were investigated based on the proximate, ultimate, and compositional analysis of pulverized samples of the *PA* biomass to determine their physical, thermal, and chemical properties towards assessing their potential for valorization to bioenergy. The lignocellulosic materials were characterized by scanning electron microscopy, energy dispersive X-ray, Fourier transform infrared spectroscopy, thermogravimetric analysis, and X-ray diffraction. The results show that the pulverized sample wastes have porous structures with varying degrees of crystallinity (wood: 89.20 %, bark: 23.90 %, leaves: 32.48 %, pods: 23.08 %), suggesting different susceptibilities to conversion processes. Notably, the wood sample had the lowest moisture content (3.13 %), and the pod sample had the highest volatile matter content (75.83 %), indicating a high potential for biofuel production. The higher heating values (HHV) and lower heating values (LHV) of the samples ranged from 15.23 to 20.49 MJ/kg and 13.83 to 18.79 MJ/kg, respectively. These calorific values are competitive with established lignocellulosic bioenergy feedstocks, positioning PA biomass as promising candidates for solid biofuel applications.

CHAPTER SIX

VALORIZATION AND OPTIMIZATION OF PROSOPIS AFRICANA POD AND COWPEA HUSK WASTES FOR DENSIFIED HYBRID BRIQUETTE PRODUCTION

6.1 Introduction

More than 4 billion people globally lack access to modern energy for cooking [245]. In underdeveloped countries, people cook with biomass and charcoal in poorly ventilated areas. This significantly impacts the climate, the environment, and their health. Solid biofuels, encompassing firewood, charcoal, residues, and dung, exhibit significant heterogeneity in content and combustion behavior [246]. Biomass is a promising eco-friendly alternative renewable energy source, and they are primarily utilized in developing countries, and accounts for over 80 % of energy demand in Africa, primarily for cooking [247]. Approximately 30 % of thermal energy in developed nations, such as Austria is derived from various forms of solid biofuels, such as logwood, wood chips, and pellets [248]. Beyond size reduction and drying Traditional conventional biofuels often undergo minimal processing [249]. The advent of modern processed biofuels, exemplified by wood chips and pellets, emerged after the 1970s oil crisis [250]. Wood chips are widely utilized in district heating and industrial applications. The pellets made from different biomass sources have acquired global acceptability as a sustainable solid biofuel in the global energy market. However, the efficient and sustainable utilization of biomass remains challenging, requiring consideration of raw material availability, quality, pricing, conversion technology, operational and maintenance aspects, and sustainability considerations such as reforestation, carbon depletion, and land use change [251], [252].

The transition toward alternatives to fossil fuels, such as bioenergy, hydropower, wind, solar, and green hydrogen, represents a promising chance to address long-standing energy poverty in developing countries and regions. Sub-Saharan Africa accounts for a significant portion of the world's population lacking access to electricity, with about 600 million out of 800 million affected due to insufficient investment, outdated infrastructure, poor governance, and a shortage of skilled personnel [253]. According to the study [9], Africa's consumption of primary fuels, excluding coal and solid biomass, is projected to rise in the future years. The modern primary energy supply is forecast to grow by 3 % each year until 2030, while the total primary energy supply is expected to fall by 13 %, primarily.

Raw material availability, quality, and pricing are the critical success factors for biomass initiatives, which necessitate substantial investments [254], [255]. Despite a favorable assessment of resource potential, sustained availability is not guaranteed, emphasizing the importance of considering prospects. Logistic chains are key to supply cost, and raw material quality should align with the desired final product standards [256], [257]. Although, lower-quality pellets may initially find a market; global trends suggest a shift toward demand for high-quality wood pellets [258]. Various costs are associated with conversion technologies, ranging from affordable cookstoves to expensive modern power facilities. Fuel suitability, emissions, and efficiency are among the factors that influence pricing. In some countries such as Germany, the implementation of stringent regulations leads to the production of costly equipment that is both efficient and low-emission [259]. Conversely, implementing less stringent regulations and reduced labor costs may lead to the adoption of cheaper, labor-intensive systems. These systems may have disadvantages, including increased emissions, lower efficiency, safety hazards, and reduced availability [260]. The combustion of Solid biofuel is complicated by the presence of non-combustible fractions, causing abrasion, slagging, and contamination. The complexity is further compounded by the need to account for solid particle emissions and residue disposal. Therefore, the proposed technologies must be proven, and suitable for the biomass pyrolysis and gasification target market [261].

The biomass briquettes are suitable energy sources for cooking, electricity, and heating. Therefore, developing nations must integrate biomass (waste) valorization for biofuel production into their energy mix policies. This is due to the significant potential of biomass to provide energy for rural communities and the urban poor as an alternative fuel, as well as in other remote areas where energy resources are scarce [262]. In Nigeria, agricultural biomass wastes could be essential energy resources. They can be converted into densified solid biofuel for clean cooking in rural areas, thereby facilitating Nigeria's transition to cleaner energy and decarbonization of its economy [19]. This is because decarbonization has been identified as a solution to climate change mitigation. These biomass wastes are abundant in developing countries and offer the potential to be used in various applications, including bioenergy production, composting, and agricultural soil improvement. Biomass fuel has been widely recognized to have net-zero CO_2 emission potential. As with the development of biomass briquette fuel in China, it has been instrumental in the control of pollutants (SO_2, NO_X, and soot) in promoting the perception that it produces fewer pollutants when compared to fossil fuel, particularly traditional coal [263]. This would boost the sector to large-scale production. Transitioning from fossil fuels to renewables such as biofuels would require continuous and sustainable improvement in the production and efficiency of biofuels, particularly solid fuels (fuel briquettes). This could be achieved by, for example, densification, which would result in improved heating efficiency and more convenient transportability [9]. The fuel briquettes' characteristics are also enhanced by the size of the particles [10], [11], [12]. In addition, raw material sourcing, collection, perhaps pretreatment, preparation, transportation dehydrating, and pulverization are necessary before densification for fuel briquettes, which improves thermal properties and transportability and reduces the cost of labor [13]. Densification may be complete in any form or shape, with or without a binding agent; however, it is significantly more effective when conducted under high pressure to optimize energy per volume [14].

There have been several studies conducted on the characterization, valorization, and production of fuel briquettes from biomass waste such as sawdust [264], [265], coffee and wood sawdust [266], sawdust and corn cob cake [267], coffee husks [268], *Pinus spp*. [269], onion peels and tamarind shells [270], coffee husk/sawdust/khat waste/dry grass [271], cocoanut shell and corncobs [272], carbonized banana stalk and corncob [273], sorghum panicle and pearl millet [274], dried rumen contents mixed with fresh blood [275], langsat wastes/guava/rambutan[276] bamboo [277], [278], [279], rice husks [10], [280], [281], [282], [283], *Prosopis juliflora* stem and anthill soil [284]. These studies underscore the need to identify and characterize the numerous biomass waste available, especially in tropical regions, to increase the basket of potential feedstock for solid biofuel production. The quality of densified briquettes is enhanced by composites of various biomass feedstocks, as demonstrated by these studies. However, to the best of the authors' knowledge, no studies have been carried out on hybrid briquettes of cowpea husk (CPH) and *Prosopis africana* pod (PAP). Despite its abundance in North America, Central/South America, and Africa/Asia [285], the PAP and CPH have not been studied for valorization as solid biofuel (briquette or pellets). However, the cassava starch binder (CSB) has been used in the past [286]. These raw materials are abundant in sub-Saharan Africa, particularly Nigeria, and present substantial commercial potential for fuel briquettes.

The performance of briquettes is affected by various factors, necessitating studies to understand the interaction among these factors to achieve optimization. The combined impact of particle size, binding agent proportions, and densification pressure on fuel briquette production has been the subject of various studies [287]. In most cases, RSM was used as an optimization technique [288], [289], which appears to be the best for developing empirical models for predicting the performance of briquettes as a function of some process parameters and optimizing the process conditions [289]. To the authors' best knowledge, no published work has been published on the use of RSM to optimize the production of CPH/PAP hybrid briquettes. The knowledge generated by this study will contribute to the existing body of scientific knowledge and data on biofuel feedstocks, thus expanding the database of potential feedstocks to enhance biofuel production in Africa.

Therefore, this study investigates the potential of CPH-PAP hybrid briquette production by varying their proportions, particle size, binding agent, and densification pressure. The briquettes are then characterized by burning rate, water resistance, shatter index, heating efficiency, calorific value, volatile matter, ash content, fixed carbon ignition time, moisture content density, etc. The essence of varying the particle size is to evaluate the most appropriate granulometry from the feedstocks for the fuel briquette production to optimize the materials against losses during production, transportation, and storage. Furthermore, RSM was employed to understand better the impact of various combinations of factor levels on the observed property. The outcomes of this research will bolster endeavors to ensure widespread access to affordable, viable, and efficient energy. This study provides new knowledge into the potential of agricultural refuse (Prosopis africana biomass and cowpea husks) for renewable energy advancement. The study also offers insight into policy direction and scale-ups in the commercial production of fuel briquettes for clean cooking in rural and peri-urban areas of Africa, as a replacement for wood fuel which is presently the predominant fuel source.

6.2 Materials and Methods

The research involved sourcing samples, cleaning the samples, preparing the samples, production of the briquettes, characterizing and testing the performance of the briquettes, data collection, optimization using RSM, analysis, and interpretation of results as shown in **Fig. 22**.

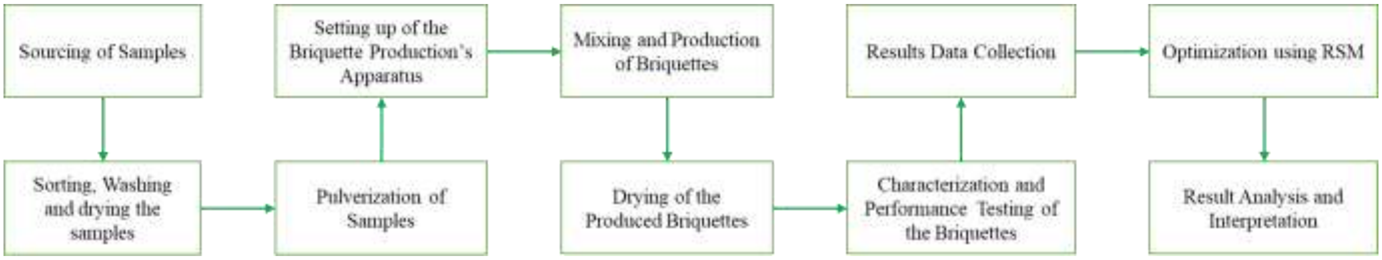

Fig. 22: PAP/CPH Briquette Production Flow Diagram

6.2.1 Materials Collection and Preparation

The *Prosopis africana,* typically found in the savannah regions of Western Africa, belongs to the *Leguminosae* family and the *Mimosoideae* subfamily [290]. It produces dark brown pods that are 5 – 10 cm long and 1 – 2 cm wide. Initially fleshy, the pods dry out as they mature, causing the seeds inside to become loose and rattle. Each pod typically contains around 15 seeds. The cowpea (*Vigna unguiculata* Walp.) is an annual leguminous crop, widely produced in Sub-Sahara Africa, America, and Asia, rich in protein, and during harvesting, generates lots of waste husk [291], [292]. The crop residues from seed production, comprising 45 - 65 % stems and 35 - 50 % leaves (sometimes roots), are cylindrical (6 - 20 cm long, 3 - 12 mm wide) and contain 8 – 20 seeds, which can be white, pink, brown, or black [292]. The two crops and their wastes are shown in **Fig. 23a** and **Fig. 23b**.The pod production is estimated to be 3000 – 4000 kg/ha in the dry irrigation treatment [293]. Cowpea husks were obtained as waste from the local farmers. In contrast, the *Prosopis africana* pod wastes were obtained from the premises of the African University of Science and Technology (AUST), Abuja, Nigeria. The *Prosopis africana* pods were washed, dried, and cracked to separate the seed; the pod wastes were then ground into smaller sizes with a jaw crusher (Model BB 50) before being pulverized with the grinder and sieved to the granulometry of 106 µm, 150 µm, 425 µm, and 1000 µm (**Fig. 23e**). In addition, the cowpea husks were pulverized with the grinder and sieved to the same granulometric classification as the PAP pulverized samples (**Fig. 23d**). Various binders, arable gum, molasses, water hyacinth, cassava starch, clay, and bentonite were considered. Cassava starch binder (CSB) was used because of its simple starch extraction method, high heating value, low price, high mechanical strength, Gelatinization and retrogradation properties, and wide availability [14] [294], with a global production of 276 million tons, predominantly produced in the Asia Pacific region, which holds approximately 75 % of the market share [294]. It was prepared by mixing the starch with distilled water at 100 ^{o}C for 10 minutes, stirring, and allowed to dissolve very well to achieve a good paste for briquetting [270]. In determining the effect of particle size in biomass production, the binder proportion (10 %), densification pressure (34.5

KN/m^2), and PAP to CPH ratio (50:50) were kept constant. For the effect of the biomass (PAP and CPH) composition, the particle sizes (150 µm), binder proportion (10 %), and densification pressure (34.5 KN/m^2) were kept constant. Also, for the determination of the effect of binder concentration in the production, the particle size (150 µm), biomass (PAP and CPH) composition (50:50), and densification pressure (34.5 KN/m^2) were kept constant. Lastly, the effect of the densification pressure on the briquette production was determined across the properties by maintaining particle size (150 µm), feedstock composition (50:50), and binder proportion (10 %) constant.

6.2.2 Composite Preparations and Experimental Designs

The PAP and CPH samples were homogeneously mixed in different proportions and particle sizes according to the design (**Table 25**). Three samples of the briquettes were prepared with varying ratios of CPH, PAP, and CSB. The densification was conducted using a 50-tonne hydraulic piston press (**Fig. 23c**) with a maximum pressure of 482.63 KN/m^2. Cylindrical molds with a diameter of 0.35m and a height of 0.25m were used for the experiment. The mixtures were transferred into the mold and compressed at a densification pressure (DP) of 34.5, 68.95, and 103.42 KN/m^2 under room temperature. The initial test was carried out with a constant feedstock composition of 50 % PAP, 10 % binder concentration, and DP of 68.95 KN/m^2. The feedstock composition was varied during the second run, with a constant particle size of 150 µm, binder concentrations at 10 %, and DP of 68.95 KN/m^2. The third run was carried out by varying the binder concentrations while maintaining the particle size (150 µm), feedstock composition (50 % PAP), and DP (68.95 KN/m^2) constant. The final run was conducted to evaluate the effect of DP on the briquette properties. The particle size (150 µm), feedstock composition (50 % PAP), and the binder concentration (10 %) constant, and the DP was varied between 34.5, 68.95, and 103.42 KN/m^2 Six briquettes were produced for each sample. After densification, each briquette sample's diameter, height, and weight were measured [266]. The properties of the produced briquettes (**Fig. 23f**) were tested after they were allowed to cure for 7 days.

Table 25: Experimental design for the predictive modeling of hybrid briquette

<table>
<tr><th colspan="5">Test for the effect of Particle Size (µm)</th></tr>
<tr><td></td><td>Densification Pressure (KN/m^2)</td><td>Binder Concentration (%)</td><td>Particle Sizes (µm)</td><td>Feedstock Composition (%)</td></tr>
<tr><td>Run 1</td><td>68.95</td><td>10</td><td>2360</td><td>(50:50)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>1000</td><td>(50:50)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>425</td><td>(50:50)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>150</td><td>(50:50)</td></tr>
<tr><th colspan="5">Test for the effect of Feedstock Composition (PAP: CPH) (%)</th></tr>
<tr><td></td><td>Densification Pressure (KN/m^2)</td><td>Binder Concentration (%)</td><td>Particle Sizes (µm)</td><td>Feedstock Composition (%)</td></tr>
<tr><td>Run 2</td><td>68.95</td><td>10</td><td>150</td><td>(90:10)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>150</td><td>(70:30)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>150</td><td>(50:50)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>150</td><td>(30:70)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>150</td><td>(10:90)</td></tr>
<tr><th colspan="5">Test for the effect of Binder Concentration (%)</th></tr>
<tr><td></td><td>Densification Pressure (KN/m^2)</td><td>Binder Concentration (%)</td><td>Particle Sizes (µm)</td><td>Feedstock Composition (%)</td></tr>
<tr><td>Run 3</td><td>68.95</td><td>12</td><td>150</td><td>(50:50)</td></tr>
<tr><td></td><td>68.95</td><td>10</td><td>150</td><td>(50:50)</td></tr>
<tr><td></td><td>68.95</td><td>6</td><td>150</td><td>(50:50)</td></tr>
<tr><td></td><td>68.95</td><td>4</td><td>150</td><td>(50:50)</td></tr>
<tr><th colspan="5">Test for the effect of Densification Pressure (KN/m^2)</th></tr>
<tr><td>Run 4</td><td>Densification Pressure</td><td>Binder Concentration</td><td>Particle Sizes</td><td>Feedstock Composition</td></tr>
</table>

(KN/m^2)	(%)	(µm)	(%)
103.42	10	150	(50:50)
68.95	10	150	(50:50)
34.5	10	150	(50:50)

Fig. 23: Briquette-making process; (a) Biomass waste extraction of cowpea husks, (b) Biomass waste extraction of *Prosopis africana* pod, (c) Experiment molds and hydraulic press, (d) pulverized cowpea husks, (e) pulverized *Prosopis africana* pod, (f) the production of CPH-PAP-CSB briquettes

6.2.3 Briquette Production Process Optimization

Optimizing the briquette production process leads to maximized efficiency, reduces the cost of iterations, and enhances quality by efficiently utilizing raw materials. These processes can contribute to the sustainability and quality of the biomass fuel industry, by evaluating binder materials, formulating binder mixtures, evaluating production equipment, and property assessment. In addition, they can be used to ensure consistency and quality. In terms of scalability, the profitability of these processes will be influenced by the economy of scale. To achieve optimal production in a large-scale biorefinery, it is necessary to evaluate the risks associated with feedstock availability, storage, and preservation. Thus, **Table 26** shows the various optimization steps that were considered during the production of the PAP-CPH Briquettes.

Table 26: Production Optimization of Biomass Briquettes (POBB)

S/N	Stage	Description
1	Raw Material Selection	In addition to the PAP under investigation, CPH was selected because it possesses promising high energy values such as high Carbon, Hydrogen, Oxygen, and low Nitrogen contents in addition to a higher heating value of 15.18MJ/kg [295]. Furthermore, it has not been extensively exploited despite its high abundance and widespread availability and accessibility. Cassava starch was selected based on its accessibility, availability, high combustion properties, and eco-friendly quality in comparison to other binders.
2	Size Reduction	Particle size is a critical factor in the production of high-quality briquettes; however, to achieve a range of sizes up to 150 µm, 425 µm, 1000 µm, and 2360 µm, various grinders were used to achieve comparable raw materials sizes, thereby simplifying the process.
3	Drying	The unprocessed materials were air-dried and subsequently assisted with oven drying 28 °C for 72 h as high-quality briquettes should have low moisture content. However, the effect of particle sizes, binders, composition, and DP will be evaluated on the moisture content, ash content, volatile matter, and fixed carbon.
4	Mixing	To enhance the cohesion and combustibility of the dried biomass vigorous stirring and blending were carried out to achieve uniform briquettes.
5	Compression	It is imperative to understand the densification pressure at any given moment, as the majority of briquette devices in Nigeria are not gauged. Consequently, it was guaranteed that the briquette machine employed in this investigation was accurately calibrated and free of any errors.
6	Curing	The shape and durability of the briquettes were preserved by allowing them to be cured

		under normal atmospheric conditions.
7	Quality Testing	The physical, mechanical strength, and combustion tests and evaluations were compared to those of previous studies conducted within the last 10 years.
8	Packaging and Distribution	Packaging, durability, and transportability to end-users or distribution points were all considered. Additionally, it was observed that the cassava flour in the composition attracted rodents, necessitating the implementation of storage strategies.
9	Result Analyses	The results were analyzed graphically using Origin 2019 and for the response surface methodology using software such as Minitab 17, MS Excel 2018, and Design Expert (version 13).

6.2.4 Physical and Mechanical Properties Analyses

Compressed and Relaxed Density

Briquette densities were determined by calculating the mass ratio per volume of briquette. The briquette compressed density (CD) was measured immediately after densification (**Eq. 1**), while the relaxed density (RD) was calculated (**Eq. 2**) after drying in the sun according to ASTM D5373 standard [296] for seven (7) days. The diameter and height were measured using a vernier caliper, and the ratio of CD to RD was calculated as Relaxation Ratio, RR (**Eq. 3**)

$$CD = {}^{W_c}/_{V_c} \tag{1}$$

$$RD = {}^{W_r}/_{V_r} \tag{2}$$

$$RR = \frac{CD}{RD} \tag{3}$$

where W_c is the weight of the briquette immediately after molding, and V_c is the volume of the briquette after molding. W_r is the weight of the briquettes after drying, and V_r is the volume of the briquette after drying.

Proximate Analyses

The moisture content (MC) was determined using (**Eq. 4**) by weighing the briquette mass sample (W_1) before placing it in a silica crucible of a known weight and dried in an oven with a set temperature of 105 °C ±3 °C for 24 h based on the ASTM D2444-16 standard [271]. It was allowed to cool to average room temperature before being re-weighed and labeled as W_2.

$$\% \, MC = \frac{W_1 - W_2}{W_1} * 100 \tag{4}$$

The percentage volatile matter content (VMC) was determined using **Eq. 5** based on ASTM D3175-18 by placing 1.5 g of the briquette sample in a crucible and subjected to a temperature of 925 ^{o}C ± 5 °C for 8 mins. The weight of the sample was then measured after cooling [271].

$$\% \, VMC = \frac{W_2 - W_3}{W_2} \tag{5}$$

where W_2 is the weight of the oven-dried sample (g); W_3 is the weight after 8 min in the furnace at 925 °C.

The ash content was evaluated using the ASTM (D3174-12) method. To achieve this, 1.5 g of the briquette samples (W_3) were placed in a closed furnace and burnt completely. The mass of the remaining material was determined (W_5), and the proportion of this mass to the original sample mass represents the quantity of ash present (**Eq. 6**).

$$\% \, Ash \; Content = \frac{W_4}{W_5} * 100 \tag{6}$$

Fixed Carbon (% FC) of the Briquettes was determined by calculation [70] (Eq. 7)

$$Fixed \; carbon \; = \; 100 \,\% \; - (\% \, MC \; + \% \, VMC + \% \, AC) \tag{7}$$

Durability/Tumbling Resistance (TR)

According to the British Standards for Fuels (EN 15210-1: 2009), a sieve shaker was used. The initial known weights of briquette samples were placed in the sieve shaker, then covered with the lid, and vigorously shaken for 15 min [264]. The weight of the briquettes was measured after tumbling to compute the weight loss (WL) and the durability/tumbling resistance (TR) as shown Eq. 8 and Eq. 9 respectively.

$$\%\,\mathrm{WL} = \frac{\mathrm{Wt_i} - \mathrm{Wt_t}}{\mathrm{Wt_i}} * 100\ (\%) \tag{8}$$

$$\%\,\mathrm{TR} = 100 - \%\,\mathrm{WL} \tag{9}$$

where $\mathrm{Wt_i}$ and $\mathrm{Wt_t}$ are the briquettes' initial weight before tumbling and the final weight after tumbling, respectively.

Stability Test (ST)

The stability test was conducted by measuring the length and diameter of the briquette samples immediately after densification and 96 h after removal from the mold [264]. The average values were calculated at 3 locations on each sample using a vernier caliper. The longitudinal and lateral stability are shown in **Eq. 10** and **Eq. 11**.

$$\%\,\Delta\mathrm{L} = \frac{\mathrm{L_0} - \mathrm{L_1}}{\mathrm{L_1}} * 100\ \ (\%) \tag{10}$$

$$\%\,\Delta\phi = \frac{\phi_0 - \phi_1}{\phi_1} * 100\ \ (\%) \tag{11}$$

where, L_o and L_1 in millimeters (mm) represent the lengths immediately after removal from the mold and the length after 96 h of removal from the mold. Furthermore, Φ_o and Φ_1 in mm represent the lengths immediately after removal from the mold and the length after 96 h of removal from the mold respectively.

Water Resistance (WR) Capacity

The WR capacity (**Eq. 13**) of the briquettes was evaluated by immersing the briquette in a container filled with water. The starting weight of the briquette before immersion (M_1) and the final weight after immersion (M_2) were measured to calculate the WR.

$$\%\ \text{Water Absorbed} = \frac{M_2 - M_1}{M_1} \tag{12}$$

$$\text{Water Resistance Capacity}\ \% = 100 - \%\ \text{Water Absorbed} \tag{13}$$

Impact Resistance and Shatter Index (SI)

The impact resistance index (IRI) was evaluated using ASTM standard D440 for drop shatter testing of coal [287], [297]. Each briquette sample was subjected to multiple drops from two meters onto a concrete surface. The quantity of droplets (Ɛ) required for the fracture of each briquette was recorded. The IRI was subsequently calculated (**Eq. 14**).

The SI was calculated using the ASTM standard D440 procedure [297]. It involved dropping the briquettes from a height of 0.6 m onto the ground. Subsequently, the fragmented briquette was weighed and measured. The percentage loss was calculated using (**Eq. 15**).

$$\text{IRI} = {}^{\varepsilon}/_{\mu} * 100 \tag{14}$$

$$\text{SI} = 100 - \text{Total Weight Loss} \tag{15}$$

where,

$$\text{Total Weight Loss} = \frac{\rho_1 - \rho_2}{\rho_1} * 100 \tag{16}$$

where μ represents the number of pieces weighing up to 5 % or more of the initial mass of the briquette after Ɛ drops, and ρ_1 and ρ_2 represent the initial briquette and weight after fragmentation, respectively.

Compressive Strength (CS)

The CS of briquettes was evaluated using an INSTRON 3382 universal testing machine equipped with a 50 kN load cell. The testing was conducted at a 1 mm/min crosshead speed following ASTM D2166-85 standards until the briquette structure failed. The maximum force endured by the briquette was recorded, and the CS was calculated using Eq. 17 [297].

$$\text{Compressive Strength} = \frac{\text{Applied Force (F)in Newton (N)}}{\text{Area of briquettes, } \ \text{A} \ (\text{m}^2)} \tag{17}$$

6.2.5 Thermal and Combustion Performance Evaluations of the Hybrid Briquettes

Ignition Time (IT)

The briquette samples were ignited at the edge of their bases with a Bunsen burner. The time taken for each briquette to ignite was recorded by IT using a stopwatch. The IT [271] was calculated using the **Eq. 18**.

$$\text{Ignition Time (IT)} = \ \text{t}_1 - \ \text{t}_0 \tag{18}$$

where t_1 is the briquette IT (seconds), and t_0 is the burner lighted time (seconds).

Burning Rate (BR)

The BR (**Eq. 19**) were determined from the ratio of mass lost during combustion to the total time taken. To determine the BR of the briquettes (**Eq. 19**), each briquette was placed on a steel wire mesh grid supported by three points, enabling unrestricted airflow. Subsequently, this setup was then placed onto a digital mass balance. The briquette was ignited from the top, and the mass loss was recorded at 10-second intervals [297].

$$\text{Burning Rate (BR)} = \frac{\text{Q (g)}}{\text{T (mins)}} \tag{19}$$

Water Boiling test to determine the Specific Fuel Consumption (SFC)

A water boiling test was conducted to evaluate the suitability of the briquettes for domestic cooking [298]. Each briquette sample, weighing 83 g, was placed on a metal domestic briquette burner to heat one liter of water in an aluminum pot, following the process outlined by [14]. Parameters such as the boiling time of the water, temperature, residual ash, and remaining briquette were measured and used for analysis. **Eq. 20** demonstrates the SFC by calculating the ratio of the mass of the briquettes burned to the amount of water required for boiling.

$$\mathrm{SFC} = \frac{\mathrm{Q\ (g)}}{\mathrm{V\ (mL)}} \qquad (20)$$

where Q is the mass of burning briquettes (g), and V is the volume of boiling water (mL).

Calorific Heating Value (HV) of the Briquettes

HV is determined by using an oxygen bomb calorimeter. However, the HV [11] is computed based on the MC, ash content, and VMC using **Eq. 21**.

$$\mathrm{HV} = (354.3 * \mathrm{FC}) + (170.8 * \mathrm{VMC}) \qquad (21)$$

6.2.6 Analysis of Variance (ANOVA) and Optimization of the Briquettes Production Using Response Surface Methodology

The central composite design feature was utilized to build an experimental design using RSM [299]. Design Expert (version 13) software was used to model the RSM, where the optimal values of dependent variables (MC, VMC, ash content, FCC, RD, TR, SI, CS, BR, IT, WR, SFC, and the HV were determined for all the samples for the scenario effects. The design (**Table 25**) resulted in sixteen (16) runs with the independent parameters (particle size, binder concentration, feedstock composition, and densification pressure), and the briquette properties (dependent variables) as the response. These factors (independent variables) were evaluated against each response [287], [300]. In this observation, the polynomial regression surface (PRS) model for the properties is a function of feedstock composition, binder concentration, densification pressure, and particle sizes. The empirical mathematical rendition is represented as shown in **Eq. 22** below.

$$\boldsymbol{PRS = \gamma_0 + \sum_{i=1}^{4} \gamma_i(X_i) + \sum_{i=1}^{4} \gamma_{ii}({X^2}_i) + \sum_{i=1}^{4} . \sum_{i+1}^{4} \gamma_{ij}(X_i * X_j)} \qquad (22)$$

where γ_o is the constant coefficient, γ_i is the linear coefficient, γ_{ii} is the coefficient of interactions, γ_{ij} is the quadratic coefficient, and X_i, X_j are the coded values of the composite briquette preparation variables. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients (Ossei-Bremang et al. 2024). The 3D view of response surface contour plots shows the briquette properties as a function of various combinations of independent variables, namely particle sizes (D), feedstock composition (A), binder concentration (B), and densification pressure (C). The surface plots are presented as a function of two factors simultaneously, keeping other factors fixed at zero.

6.3 Results and Discussion

The empirical findings on the effect of the densification of hybrid biomass of *Prosopis africana* pod wastes and cowpea husks are presented in **Table 30**.

6.3.1 Effect of Particle Sizes on Briquette Properties

Keeping the composition (50:50), binder (10 %), and DP (68.95 KN/m^2) constant, the results of the effect of particle sizes on hybrid briquette properties are presented in **Fig. 24**. The briquettes with particle sizes of 150 µm exhibited smooth texture and better appearance (**Fig. 23f**). The briquettes exhibited the highest compressed density (1.09 kg/m^3), and RD (0.79 kg/m^3) for this particle size. The RR also decreased with decreasing particle sizes, which indicates that the briquette becomes more stable during handling, storage, and packaging, owing to significant volume displacement [273]. This validates the earlier studies that briquettes produced at < 500 µm particle sizes are more stable [273] as indicated by results obtained from the 425 and 150 µm measurements. The proximate analysis examining the impact of particle size on compaction revealed that the MC of the hybrid briquette was reduced while the VMC increased as the particle size decreased. With variation in particle sizes, and contrary to the study [298], there was an inverse proportionality relationship between MC and densities, notwithstanding the difference in particle sizes. This phenomenon can be explained by the application of DP, which causes the pores and micro-gaps to close, thereby preventing water from saturating the material.

The result showed that the WR was highest (89.56 %) when the particle size was lowest, the SI (0.96). The VMC is the amount of biofuel that is released as gases when it is heated. This implies that a sample with a higher VMC has a greater propensity for rapid combustion and easier ignition. This validates the increasing ignition time with a decrease in particle size. The result further shows that the HV increased with decreasing particle sizes. **Fig. 24** displays the contour plots of the mechanical properties for handling. There was no significant variation in the CS at lower particle sizes; this capacity of the briquette to withstand crushing load was slightly higher (7.129 KN/m^2) with the particle sizes of 1000 µm and 150 µm compared to 425 µm. However, the particle of 2360 µm recorded a low CS (3.775 KN/m^2). This drop in particle size leads to a reduction in both BR and SFC. Porosities in larger particle sizes facilitate efficient air [10]. The lowest BR (0.524 g/min) and SFC (0.235 g/l) were achieved at particle size 150 µm, whereas the ignition time increased with decreasing particle sizes. After the ignition, 425 µm and 150 µm exhibited a blue flame at 1.5 mins and 1.95 mins, respectively. In contrast, larger particle sizes of 2360 µm and 1000 µm produced yellowish-orange flames at 2 mins and 2.77 mins, respectively. This implies that briquettes with lower fine particle sizes will be better for cooking and heating.

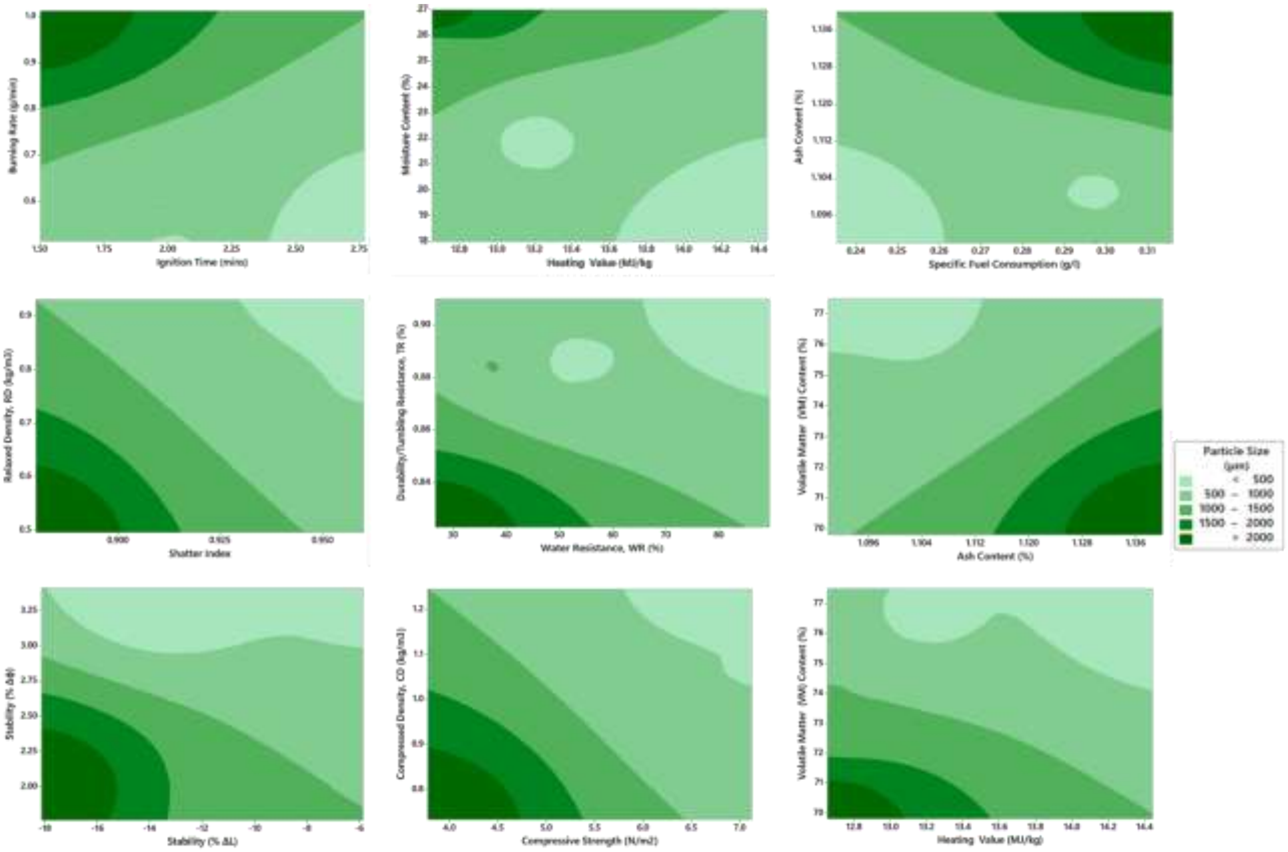

Fig. 24: Contour Plots of the effect of particle sizes on the mechanical properties and combustion evaluation of briquettes

6.3.2 Effect of Feedstock Composition on Briquette Properties

To evaluate the effect of the different compositions of the biomass wastes (PAP and CPH), a 150 µm particle size was used and kept constant, showing better mechanical and combustion properties. Furthermore, the binder concentration and DP were kept constant at 10 % and 34.5 KN/m^2, respectively. **Fig. 25 (a-b)** shows that the briquette with 50 % PAP exhibited the highest volatile matter (77.5 %) and lowest MC (18 %) compared to other ratios. The reduced moisture level will enhance the ability to ignite. For the HV, the 50 % PAP composition yielded the highest value (14.45 MJ/kg), while the BR was relatively high at 0.514 g/min. However, the 10 % PAP had the maximum heating value (0.560 MJ/kg). The compressed density was relatively higher at 1.24 kg/m^3 compared to other ratios. The briquette with a PAP content of 90 % exhibited the highest level of WR, measuring 93.10 %. Further analyses of the material handling revealed that the 50 % PAP sample has the highest TR, with 88.63 %.

Additionally, it displayed an HV of 14.45 MJ/kg, and the ignition time had a comparatively high value for other ratios.

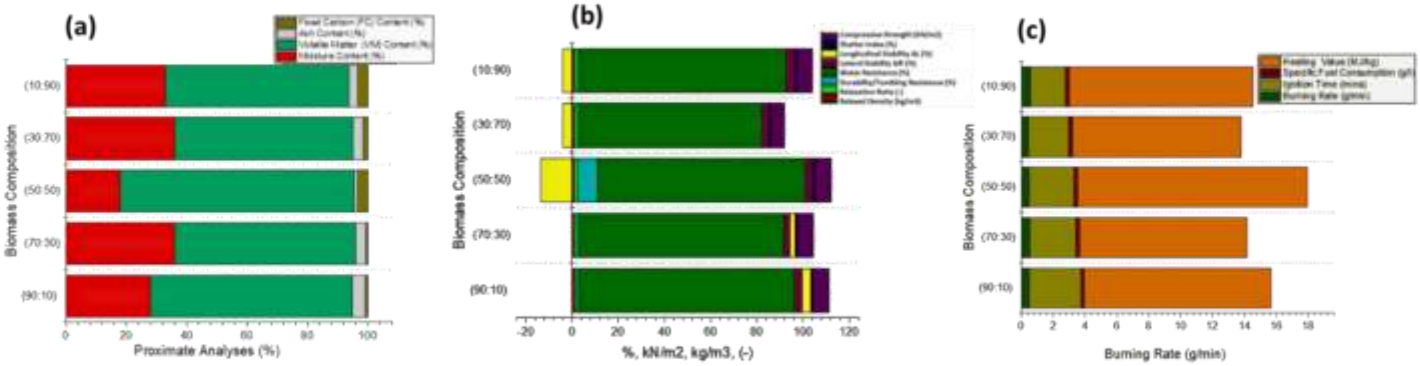

Fig. 25: Effect of feedstock composition (PAP: CPH) on (a) Proximate analyses of the briquettes, (b) Mechanical properties of the briquettes, and (c) Combustion properties of the briquettes

6.3.3 Effect of Binder on Briquette Properties

The 150 µm particle size and 50:50 sample composition were maintained at a DP of 68.95 KN/m^2 to determine the impact of binder concentrations on briquette productions, considering the observations in sections 3.1 and 3.2. The results indicated that the properties of the briquette were influenced by the concentration of the binder (cassava starch). The contour plot (**Fig. 26**) of the resulting properties showed that the MC was lowest (12 %) at the highest binder concentration (12 %). Conversely, the highest binder concentration gave the highest VMC (79 %). The compressed form of briquettes with the highest binder (12 %) has the largest density (1.82 kg/m^2). The lowest binder concentration (4 %) was 0.72 kg/m^2 and 0.33 kg/m^2 in the relaxed state (1.68 kg/m^2). The SI, TR, RD, and compressed density all decreased as the binder concentrations decreased. The highest ignition time (2.85 mins) and lowest BR (0.59 g/min) were observed at the maximum binder concentration (12 %).

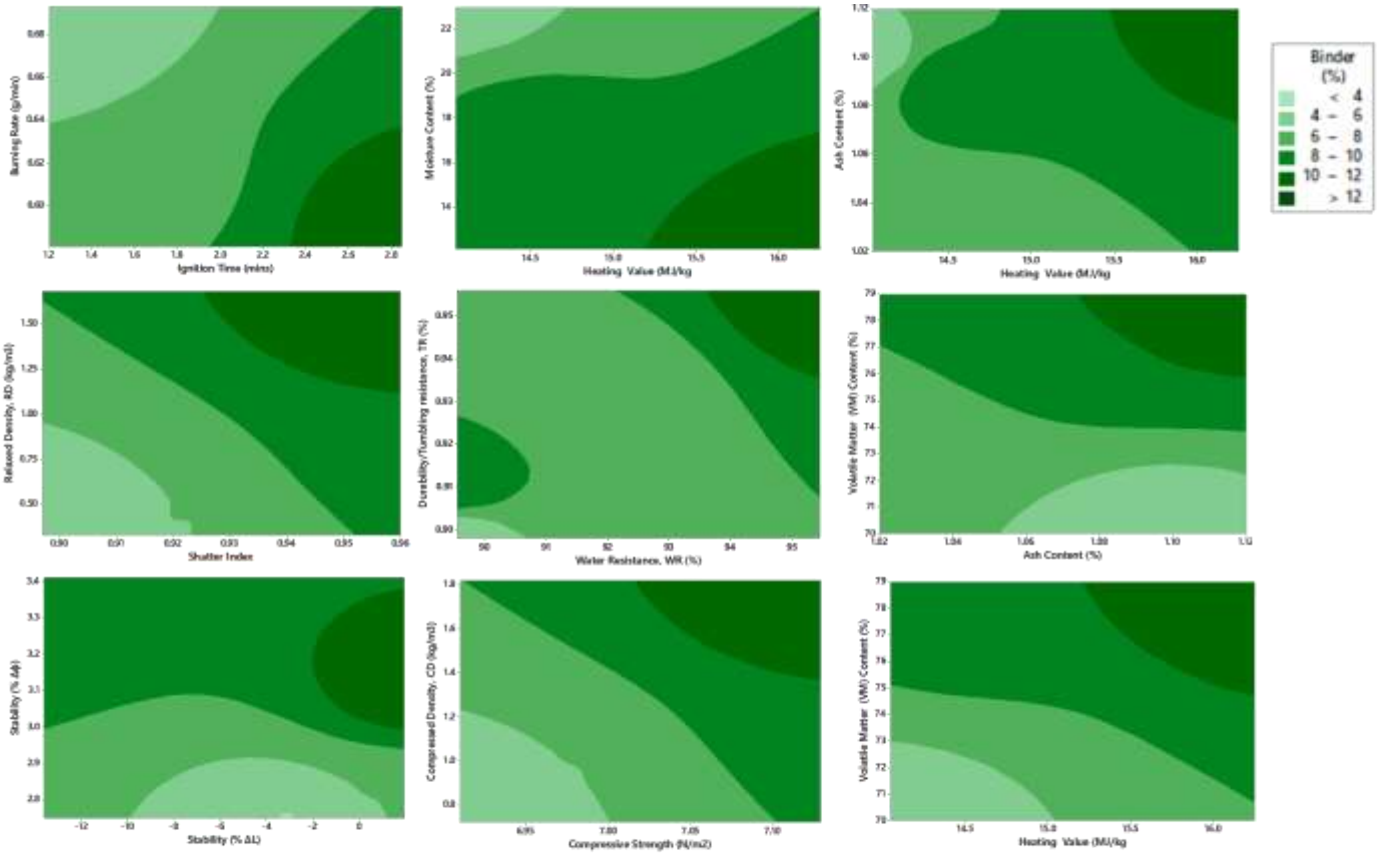

Fig. 26: Contour Plots of the effect of binder on the mechanical handling and combustion evaluation of briquettes

6.3.4 Effects of Densification Pressure on Briquette Properties

As demonstrated on **Fig. 27**, the impact of pressure on briquette qualities during compaction revealed that pressure of 34.5 KN/m^2 resulted in the highest levels of MC (21 %) and VMC (78 %). The maximum pressure recorded was 103.42 KN/m^2, with values of 10 % and 77.2 % respectively. The pressure measurement indicated the greatest levels of ash content (1.1 %) and FCC (11.7%). Regarding mechanical handling, the briquette exhibited the highest resistance to tumbling at a pressure of 103.42 KN/m^2, indicating its durability at a rate of 98%. The CS was relatively close, measuring 7.21, 7.13, and 7.11 kN/m^2 for 103.42, 68.85, and 34.5 KN/m^2 respectively. The WR (92.11 %) was significantly higher when the DP reached 103.42 KN/m^2.

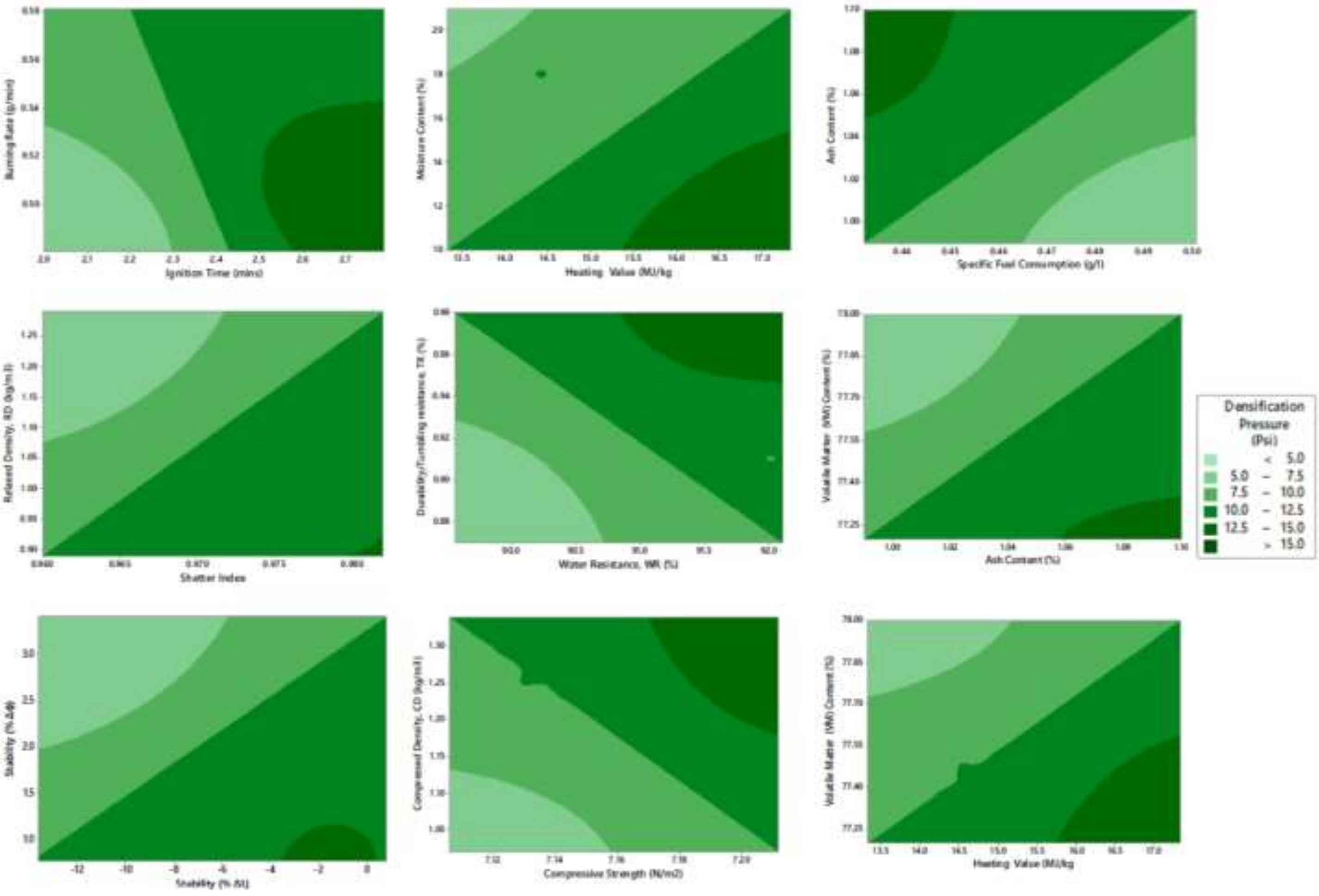

Fig. 27: Contour Plots of the effect of densification pressure on briquettes' mechanical properties and combustion evaluation

6.3.5 Statistical and Optimization of the Briquette Properties

To identify the most suitable parameters to produce fuel briquettes, it is necessary to evaluate the characteristics that have a substantial impact on the reaction to proximate analysis results.

Modeled and Optimal Moisture Content (MC)

The examination of the quadratic MC model produces significant results, indicating that the model accurately represents the data. The F-value of the model (17.78) is extremely significant (p-value < 0.0001) (**Table 27**), suggesting that the model explains a substantial portion of the variability in the MC. Furthermore, there is only a very small probability (0.01 %) that this high F-value is due to random noise. The study examined the composition of A, C, as well as the interaction between AC, AD, BC, and B^2, all of which were determined to be significant ($p < 0.05$) in accordance with [300]. In contrast, variables B (Binder), AB, BD, CD, A^2, C^2, and factor D^2 do not have a significant impact ($p > 0.1$). The Lack of Fit tests results in a p-value of 0.6164, indicating that it is insignificant relative to pure error, suggesting that the model fits the data accurately. The fit statistics show that the model has a high coefficient of determination ($R^2 = 0.9432$), indicating that the model accounts for 94.32 % of the variation in the MC. The adjusted R^2 value (0.8901) suggests that the model has a good ability to predict outcomes. In addition, the predicted R^2 (0.7638) is reasonably like the adjusted R^2, indicating that the model is reliable for predicting MC. Furthermore, the precision value of 16.53 indicates a satisfactory signal-to-noise ratio, which ensures the model's reliability in navigating the design space. The ANOVA study confirms the statistical significance of the quadratic model (**Eq. 23**) for MC. It reveals that the model can accurately predict MC based on the parameters that were evaluated. The coefficients represent the relative impact of each factor and interaction, with higher coefficients signifying a more substantial effect on MC.

$$MC_b = +5.56 + 5.27\mathrm{A} + 0.63\mathrm{B} - 6.03\mathrm{C} + 0.99\mathrm{D} + 2.08\mathrm{AB} + 6.78\mathrm{AC} + 2.85\mathrm{AD} - 7.7\mathrm{BC} + 0.78\mathrm{BD} + 0.93\mathrm{CD} + 0.15\mathrm{A}^2 + 3.53\mathrm{B}^2 + 0.36\mathrm{C}^2 - 0.62\mathrm{D}^2 \quad (23)$$

When the A, B, C, and D were combined, the optimal MC was determined to be 4.87 %. **Fig. 28** shows the impact of combining two independent variables on the MC through the contour and 3D-surface plots. The MC is slightly affected by the B and D, as evidenced by their low coefficients and non-significant p-values. The MC is considerably affected by C, as demonstrated by its negative coefficient. The interactions between factors (AC, AD, BC, and B^2) also have a significant impact on MC. Simultaneously, the higher-order terms (AB, BD, CD, A^2, C^2, and D^2) have negligible impact on MC, as indicated by their high p-value.

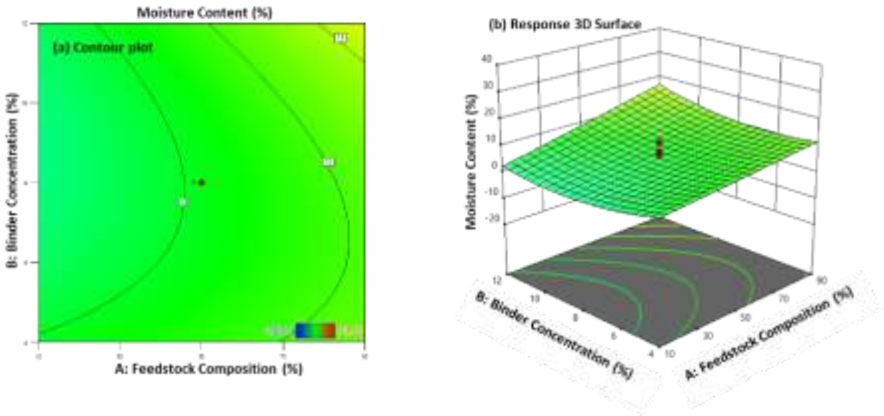

Fig. 28: Interaction plots of moisture content for briquette samples

Modeled and Optimal for Volatile Matter Content (VMC)

The result for VMC indicates that the model's overall F-value of 4.08 and p-value of 0.0041 (**Table 27**) is statistically significant, indicating that the model accurately explains the variation in VMC. However, the high model F-value suggests a low probability (0.41 %) that the results are due to random fluctuations. The predictor variables, feedstock A, C, AC, and BC have p-values < 0.05, indicating that these variables have a significant impact on the VMC. However, the variable B, C, D, AB, AD, BD, and CD do not have a significant impact on predicting the outcomes ($p > 0.1$). The fit statistics indicate that the model accounts for a significant portion of the variation in VMC as evidenced by an R^2 value of 0.6824, implying that the model explains 68.24 % of the variability in the response. The adjusted R^2 (0.5152) and predicted R^2 (0.5035) values are reasonably close, indicating a good agreement between them and suggesting the model is reliable for making predictions. The precision ratio is 8.671, greater than 4, which indicates an insufficient signal and implies that the model can navigate the design space efficiently. The ANOVA analysis suggests that the two-factor interaction (2FI) model (**Eq. 24**) provides a good fit for predicting VMC based on the values of the significant factors.

$$VMC_b = 92.20 - 6\mathrm{A} - 4\mathrm{AC} + \mathrm{AD} - 6\mathrm{BC} \tag{24}$$

The composition of the feedstock (A) and the interaction between AC, and BC have a significant impact on reducing VMC, indicating a critical influence on the briquetting process. Factors B, C, and D and their interactions (except AC and BC) had no significant impact on the response, suggesting they may be less critical. The highest VMC of 93 % was achieved by considering the particle size, feedstock composition, binder concentration, and DP. **Fig. 29** shows the impact of combining two independent variables on the VMC through the contour and 3D-surface plots.

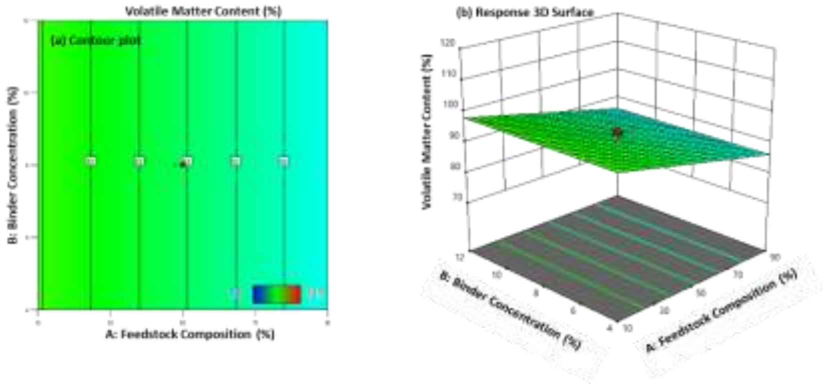

Fig. 29: Interaction plots of volatile matter content for briquette samples

Modeled and Optimal Ash Content

The ash content results demonstrate that the model (**Eq. 25**) is statistically significant and accurately fitted, as indicated by an F-value of 3.07 and a p-value of 0.0196. The significance level of p suggests that the observed F-consequence is unlikely to occur at random, with a 1.96 % probability. While analyzing these factors, it was observed that a (feedstock composition) and the interaction terms AB, CD, and A^2 have significant contributors to the variation in ash content. There is no statistically significant evidence for the impact of parameters B, C, D, AC, AD, BC, BD, B^2, C^2, and D^2. They suggest areas where model simplification could be considered. In addition, we evaluate the discrepancy and conclude that it is not significant compared to the random variation, resulting in an F-value of 1.61 and a p-value of 0.3134. This indicates that the model is a good fit for the data. The fit statistics show that the model accounts for a significant portion of the variation in ash content, with an R-squared of 0.74. The adjusted R-squared is 0.799, indicating that the model's ability to predict outcomes remains strong even after accounting for the number of factors. The predicted R-squared of 0.73 suggests reasonable agreement with the adjusted R-squared. The adequacy precision value of 28.88 indicates a satisfactory signal-to-noise ratio which confirms the model's reliability for navigating the design space. From **Eq. 25**, the baseline ash content is 1.5 %. The composition of feedstock showed a significant negative impact, while the B, C, and D had a negligible impact. The interaction Effects (AB and CD) demonstrated a significant positive impact. The A^2 shows a significant negative impact on the quadratic terms, while the other quadratic terms have insignificant impacts.

$$\begin{aligned} Ash_b = {} & 1.50 - 2.46\mathrm{A} - 1.04\mathrm{B} - 0.35\mathrm{C} - 1.23\mathrm{D} + 2.93\mathrm{AB} + 1.49\mathrm{AC} + 0.09\mathrm{AD} - 0.95\mathrm{BC} \\ & + 1.14\mathrm{BD} + 2.38\mathrm{CD} - 1.93\mathrm{A}^2 + 0.87\mathrm{B}^2 + 1.03\mathrm{C}^2 \\ & + 0.47\mathrm{D}^2 \qquad (25) \end{aligned}$$

An ideal ash percentage of 2.61 % was achieved by considering the interaction between particle size, feedstock composition, binder concentration, and densification pressure. **Fig. 30** shows the impact of combining two independent variables on the ash content using contour and 3D-surface plots.

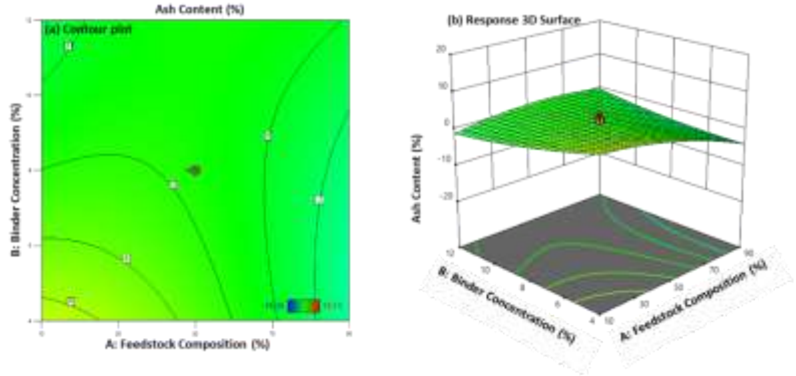

Fig. 30: Interaction plots of Ash content for briquette samples

Modeled and Optimal Fixed Carbon Content (FCC)

The results indicate that the model is highly significant (F-value = 119.70, $p < 0.0001$) and that multiple relevant predictors explain the variability in the response, suggesting that the variables under consideration significantly influence the FCC and can account for the observed variation. Specifically, the model terms AC, BC, B^2, and C^2 demonstrate statistical significance ($p < 0.05$) to the A, B, and C. The particle size (D) and other interaction terms such as AB, AD, BD, and CD, as well as quadratic terms A^2 and D^2, did not yield statistical significance. Further analysis reveals a significant lack of Fit (F-value = 0.56, p = 0.7949), indicating that the model is a good fit for the data. However, the model's high R^2 of (0.9911) and reasonable agreement between predicted R^2 (0.97) and Adjusted R^2 (0.9828) indicate that it adequately explains the variation in the FCC. The adequate precision value (40.07) indicates a strong signal-to-noise ratio, which further supports the model's reliability. Therefore, the investigation concludes that the quadratic model **(Eq. 26)** is robust and can effectively navigate the design space for optimizing FCC based on the examined variables.

$$FCC_b = 2.23 + 31.10\mathrm{A} - 10.80\mathrm{B} - 10.53\mathrm{C} + 1.25\mathrm{D} + .27\mathrm{AB} + 1.08\mathrm{AC} - 0.15\mathrm{AD} - 3.91\mathrm{BC} - 0.68\mathrm{BD} - 1.73\mathrm{CD} - 0.43\mathrm{A}^2 + 4.34\mathrm{B}^2 + 5.46\mathrm{C}^2 - 0.25\mathrm{D}^2 \tag{26}$$

A positive coefficient suggests a positive effect on FCC, while a negative coefficient suggests a negative impact. The relatively high magnitude of the coefficient indicates the strength of the impact. After considering factors such as the interaction between the particle size, feedstock composition, binder concentration, and DP, the optimal FCC of 3.31 % was determined. **Fig. 31** shows the impact of combining two independent variables on the FCC using the contour and 3D-surface plots.

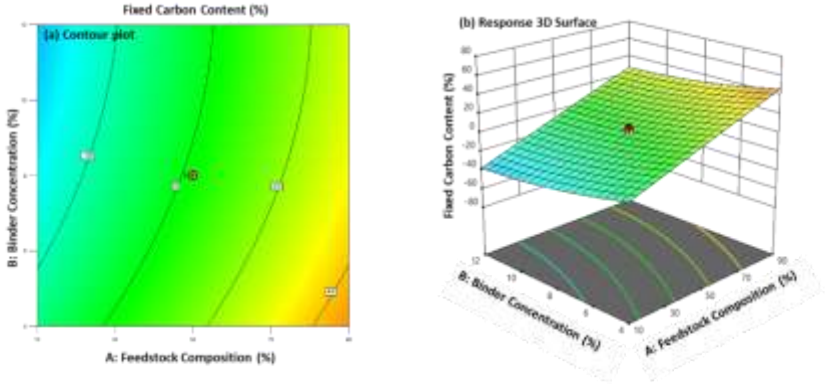

Fig. 31: Interaction plots of fixed carbon content for briquette samples

Table 27: ANOVA Results for Proximate Analyses Optimization

Source	**MC**		**VMC**		**Ash Content**		**FCC**	
	F-value	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**	**F-value**	**p-value**
Model	17.78	< 0.0001	4.08	0.00	3.07	0.02	119.70	< 0.0001
A-Feedstock Composition	42.94	< 0.0001	20.60	0.00	9.01	0.01	1204.25	< 0.0001
B-Binder	0.61	0.45	0.00	1.00	1.62	0.22	145.32	< 0.0001
C-Densification Pressure	56.21	< 0.0001	0.00	1.00	0.18	0.67	138.06	< 0.0001
D-Particle Size	1.54	0.23	0.00	1.00	2.23	0.16	1.93	0.18
AB	4.45	0.05	0.00	1.00	8.49	0.01	1.35	0.26
AC	47.46	< 0.0001	6.10	0.02	2.20	0.16	101.96	< 0.0001
AD	8.35	0.01	0.38	0.54	0.01	0.93	0.02	0.89
BC	61.46	< 0.0001	13.73	0.00	0.89	0.36	12.70	0.00
BD	0.61	0.45	0.00	1.00	1.30	0.27	0.39	0.54
CD	0.88	0.36	0.00	1.00	5.62	0.03	2.50	0.13
A^2	0.04	0.84	0.00	0.00	6.30	0.02	0.26	0.62
B^2	22.08	0.00	0.00	0.00	1.28	0.28	26.80	0.00
C^2	0.22	0.64	0.00	0.00	1.82	0.20	42.45	< 0.0001
D^2	0.67	0.42	0.00	0.00	0.37	0.55	0.09	0.77

Modeled and Optimal Compressed Density

A quadratic model was used to examine the factors that influence the compressed density of the briquettes. The results indicate that the model (**Eq. 27**) is highly significant, with an F-value of 17.77 and a p-value < 0.0001 (**Table 28)**. The feedstock composition (A), densification pressure (C), particle size (D), and interactions AB, AC, AD, and CD, as well as quadratic terms A^2 and D^2, are significant with p-values < 0.05. In contrast, the binder concentrations (B), interactions BC, BD, and quadratic terms B^2, C^2 are not significant with p-values > 0.10. The lack of fit F-value of 4.42 and p-value of 0.0573 suggests a 5.73 % probability that the lack of fit is caused by random variation. The fit statistics provide evidence for the model's adequacy, although there is little concern that it does not fit the data accurately. R^2 (0.9431) suggests that the model accounts for 94.31 % of the variance in the response variable. The adjusted R² (0.8901), predicted R² (0.6974), and adequate precision (13.13) indicate that the model is good and can be used to navigate the design space effectively.

$$CD_b = 0.89 + 1.52\mathrm{A} - 0.42\mathrm{B} + 1.17\mathrm{C} - 1.01\mathrm{D} + 1.58\mathrm{AB} + 2.97\mathrm{AC} - 1.03\mathrm{AD} - 0.17\mathrm{BC} + 0.35\mathrm{BD} + 1.89\mathrm{CD} - 2.15\mathrm{A}^2 - 0.26\mathrm{B}^2 - 0.41\mathrm{C}^2 - 2.63\mathrm{D}^2 \quad (27)$$

Again, the positive coefficients signify a positive effect on compressed density, while negative coefficients indicate a negative impact. Interaction terms (AB, AC, AD, BC, BD, and CD) suggest the combined effect of the independent variables. The composition of the feedstock and its square A² strongly impact the model. The interaction between the binder particle size, feedstock composition, binder concentration, and DP resulted in an optimal compressed density of 1.14 kg/m^3. **Fig. 32** shows the effect of combining two independent variables on the compressed densities, as displayed in the contour and 3D-surface plots.

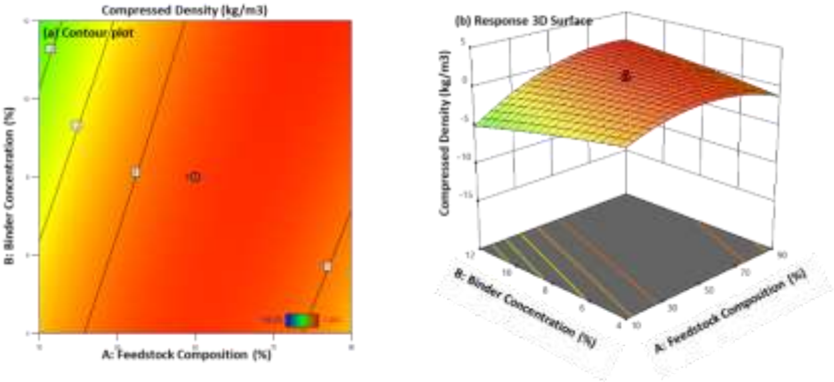

Fig. 32: Interaction plots of compressed density for briquette samples

Modeled and Optimal Relaxed Density (RD)

The results reveal that the quadratic model (**Eq. 28**) for RD is highly significant with an F-value of 7.30 and a p-value of 0.0002 (**Table 28**). This indicates that the overall model is a good fit for the data, with only a 0.02 % probability that the observed F-value is due to random variation. The B, D, and interaction AB, AD, BD, and C² are all significant and have a great influence on the RD during briquette production. The A, C, AC, BC, CD, A², B², and D² do not have significant effects (p-values > 0.1) at the same time. Lack of fit analysis indicates that the fit is not significant (p = 0.9491) relative to pure error, suggesting the model accurately represents the data without significant variations. The high R^2 value (0.8720) and sufficient precision ratio (12.44) suggest that the model is a good fit for the data well and can accurately estimate RD within the design space. The model provides valuable insights for optimizing the production of briquettes to achieve the desired RD, thereby enhancing the efficiency and effectiveness of energy solutions based on briquettes.

$$RD_b = -0.71 - 0.47A + 1.79B - 0.52C + 1.44D + 2.92AB - 0.61AC + 1.17AD - 0.11BC + 1.16BD - 0.35CD - 0.27A^2 + 0.69B^2 + 1.15C^2 + 0.24D^2 \quad (28)$$

These coefficients in **Eq. 28** represent the contribution of each factor to the RD. The positive coefficients signify a positive effect on RD, while negative coefficients indicate a negative impact. The interaction between the binder particle size, feedstock composition, binder concentration, and DP resulted in an optimal RD of 0.474 kg/m^3. **Fig. 33** shows the effects of combining two independent variables on the RD that were analyzed using contour and 3D-surface plots.

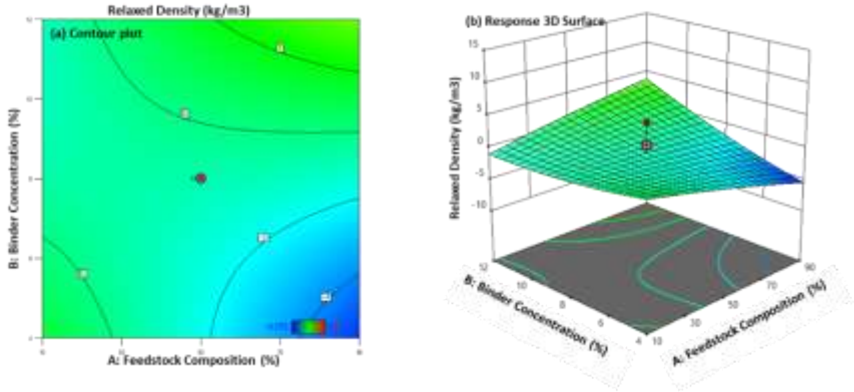

Fig. 33: Interaction plots of relaxed density for briquette samples

Modeled and Optimal Relaxation Ratio (RR)

The model for predicting RR yielded significant results (F-value = 12.62 and p-value < 0.0001), indicating that the model applies to tested factors. The presence of a 0.01% probability that the high F-value is attributed to noise further demonstrates the reliability of the model. Among the model terms, the A, B, C, BC, CD, A^2, C^2, and D^2 were observed to be significant ($p < 0.05$), indicating their influence on the RR, and should be considered when optimizing the RR. From Eq. 29, the negative coefficients for A, B, C^2, and A^2 indicate that a rise in these parameters is associated with an increase in the RR. The positive coefficients for D, BC, CD, and D^2 suggest that as these factors increase, the RR also increases. B and A^2 significantly impact the RR due to their large F-values and extremely low p-values. The lack of fit was significant, indicating that the model does not perfectly fit the data. However, the fit statistics revealed a high R^2 value of 0.9217, indicating that the model accounts for 92.17 % of the variability in the RR. The adjusted R^2 (0.8487) and predicted R^2 values (0.8294) were also high, indicating good model fit and robust predictability. The analysis suggests that the quadratic model (Eq. 29) adequately predicts the RR based on the tested factors.

$$\begin{aligned} RR_b = {} & 1.64 - 1.12\mathrm{A} - 2.40\mathrm{B} - 0.12\mathrm{C} + 0.33\mathrm{D} + 0.04\mathrm{AB} + 0.09\mathrm{AC} - 0.07\mathrm{AD} + 1.08\mathrm{BC} \\ & - 0.21\mathrm{BD} + 0.88\mathrm{CD} - 1.18\mathrm{A}^2 + 0.3\mathrm{B}^2 - 1.02\mathrm{C}^2 \\ & + 1.14\mathrm{D}^2 \qquad (29) \end{aligned}$$

The coefficients associated with each factor indicate the direction and magnitude of their impact on the RR. Again, a positive coefficient suggests a positive influence on the RR, while a negative coefficient suggests a negative impact. The most significant coefficients in absolute terms are associated with binder concentration (B) and composition of the feedstock (A), indicating they have the most significant impact on the RR. The interaction between the particle size, feedstock composition, binder concentration, and densification pressure resulted in an optimal RR of 0.99. **Fig. 34** shows the impact of combining two independent variables on the RR using the contour and 3D-surface plots.

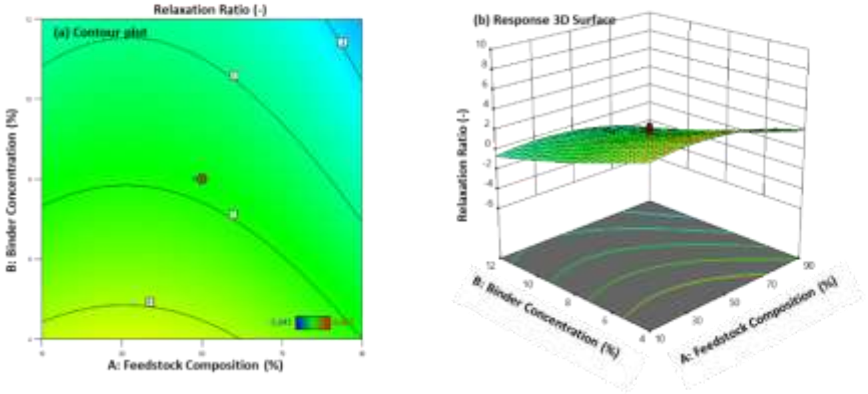

Fig. 34: Interaction plots of relaxation Ratio for briquette samples

Modeled and Optimal Durability/Tumbling Resistance (TR)

The quadratic model used for evaluating TR produced very significant results (F-value = 12.07, $p < 0.0001$), indicating that the model is statistically significant. The parameter examined included, A, B, AB, AC, CD, A^2, and B^2, which were found to be significant ($p < 0.05$). However, C, D, AD, BC, BD, C^2, and D^2 were not significant ($p > 0.05$). The Lack of Fit test indicated that the lack of fit is not significant statistically (p-value = 0.3557) compared to pure error, suggesting that the model fits well. The fit statistics demonstrate a high level of model fitness, with an R^2 of 0.927, implying that the model accounts for 92.7 % of the variation in TR. The adjusted R^2 is 0.887, suggesting that the model accounts for 88.7 % of the variability in the response variable. In addition, the predicted R^2 (0.867) is closely aligns with the adjusted R^2, indicating that the model has a good predictive ability and reliability. Adequacy precision measured by the signal-to-noise ratio 25.38, was satisfactory indicating that the model can effectively navigate the design space. The model (**Eq. 30**) establishes a relationship between the coded factors (particle size, binder, feedstock composition, and DP) and the response (TR). Each coefficient represents the effect of the corresponding factor or interaction on the response. The coefficients for variables C and D are negatively correlated with TR, indicating that increasing C and D decreases lead to a decrease in these properties. However, further investigation may be required to examine the insignificant variables and their potential impact on the model (**Eq. 30**).

$$TR_b = 0.69 + 0.35\text{A} + 0.06\text{B} - 2\text{C} - 0.6\text{D} - 1.39\text{AB} - 0.9\text{AC} - 0.37\text{AD} - 0.09\text{BC} + 0.01\text{BD} - 1.92\text{CD} - 0.53\text{A}^2 - 0.36\text{B}^2 + 1.17\text{C}^2 + 1.09\text{D}^2 \quad (30)$$

The interaction between the particle size, feedstock composition, binder concentration, and DP resulted in an optimal TR of 0.76 %. **Fig. 35** shows the impact of combining two independent variables on the TR through the contour and 3D-surface plots.

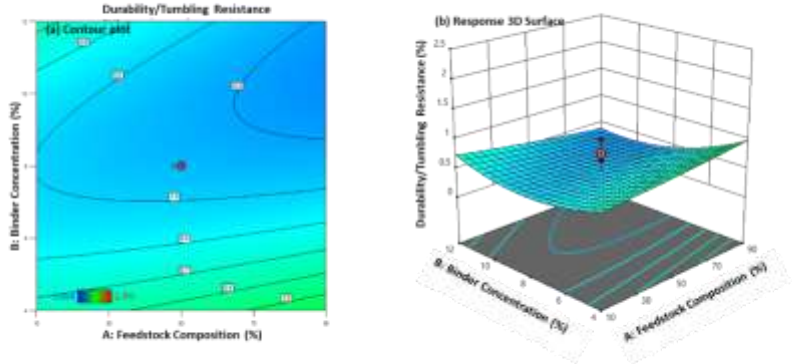

Fig. 35: Interaction plots of durability/tumbling resistance for briquette samples

Modeled and Optimal Water Resistance (WR)

The result indicates the model is highly significant with an F-value of 22.83 and a p-value of < 0.0001 (**Table 28**), indicating that the interactions AB, AC, BD, and A^2 have a significant impact on WR, while A, B, C, D, BC, CD, B^2, C^2, and D^2 do not have significant effect and therefore have less influence on WR. The lack of Fit is not statistically significant (F-value of 0.43, p-value of 0.8774), indicating good model fit. The high R^2 (0.9552) and predicted R^2 (.8454) are in good agreement with the Adjusted R^2 (0.9133), suggesting that the model is suitable and accurate. The high precision (18.47) indicates a robust signal-to-noise ratio, which enhances the reliability of prediction. The analysis suggests that the quadratic model (**Eq. 31**) is an effective tool for predicting WR, with significant factors influencing the response variable.

$$WR_b = 104.60 - 0.21\,\mathrm{A} - 0.25\,\mathrm{B} - 0.094\,\mathrm{C} + 0.34\,\mathrm{D} - 5.18\,\mathrm{AB} - 3.50\,\mathrm{AC} + 1.30\,\mathrm{AD} - 0.93\,\mathrm{BC} - 2.98\,\mathrm{BD} + 0.41\mathrm{CD} - 6.18\,\mathrm{A}^2 + 0.57\,\mathrm{B}^2 + 0.45\,\mathrm{C}^2 + 0.57\,\mathrm{D}^2 \quad (31)$$

The intercept term (104.6) represents the anticipated WR when all parameters are set to zero. The coefficient for variables A, B, C, AB, AC, BC, BD, and A^2 suggest that increasing these values decreases WR. Conversely, the coefficient for variables D, AD, B^2, C^2, and D^2 suggest that increasing these values will increase WR. The interaction between the particle size, binder concentration, DP, and feedstock composition resulted in an optimal WR of 108.3 %. **Fig. 36** shows the impact of combining two independent variables on the WR using the contour and 3D-surface plots.

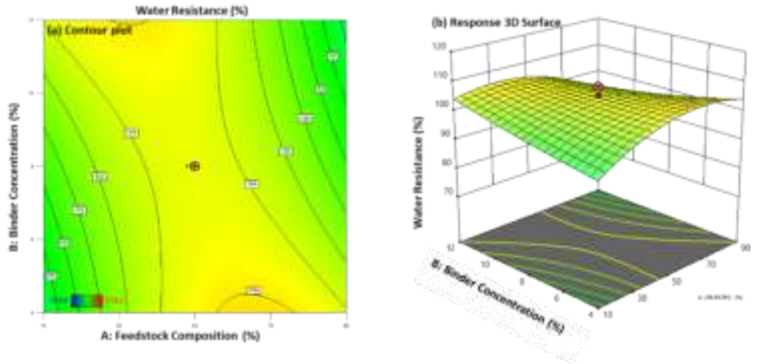

Fig. 36: Interaction plots of water resistance for briquette samples

Modeled and Optimal Lateral Stability $\Delta\phi$

The ANOVA results for a two-factor interaction (2FI) model reveal that the linear model for $\Delta\phi$ is significant with an F-value of 11.80 and a p-value < 0.0001. This implies that the model can provide a clear and accurate description of a significant portion of the variability in the response variable. The important parameters that determine $\Delta\phi$ are the A, B, D, and the interactions (AC, BC, AC, BD, and CD). The densification pressure (C) and the interactions (AD) do not significantly impact the $\Delta\phi$. The lack of fit as indicated by the F-value of 0.46 is not significant (p-value of 0.8857), suggesting that the model adequately fits the data. The fit statistics, including R^2 (0.8613) and adjusted R^2 (0.7884), indicate that the model accurately fits the data, with a satisfactory level of precision. The predicted R^2 (0.5992) is in good agreement with the modified R², suggesting the model's predictions are reliable. The high precision, shown by a signal-to-noise ratio of 15.54, indicates that the model provides valuable information relative to the variability in the data. The analysis suggests that the linear model (**Eq. 32**) is suitable for predicting Δϕ and can be effectively used for designing navigation in the given context.

$$\begin{aligned}\Delta\phi_b = {} & 0.37 - 1.59\,\mathrm{A} + 5.18\,\mathrm{B} - 0.94\mathrm{C} - 2.58\,\mathrm{D} - 2.36\,\mathrm{AB} - 1.93\,\mathrm{AC} + 0.41\,\mathrm{AD} \\ & - 1.95\,\mathrm{BC} + 2.14\,\mathrm{BD} \\ & + 3.63\,\mathrm{CD} \qquad (32)\end{aligned}$$

Eq. 32 shows that the A, B, D, and interaction terms (AB, AC, BC, BD, CD) substantially influence the Δϕ; however, the binder concentration (B) has the most substantial positive impact on the response Δϕ, followed by the interaction between densification pressure and particle size (CD). The non-significant variables (C and AD) suggest that their influence on Δϕ is negligible. Considering its high signal-to-noise ratio and reasonable predictive capability, the model is considered for navigating the design space. The interaction between the particle size, binder concentration, DP, and feedstock composition resulted in an optimal Δϕ of 3.43 %. **Fig. 37** shows the impact of combining two independent variables on the Δϕ, using the contour and 3D-surface plots.

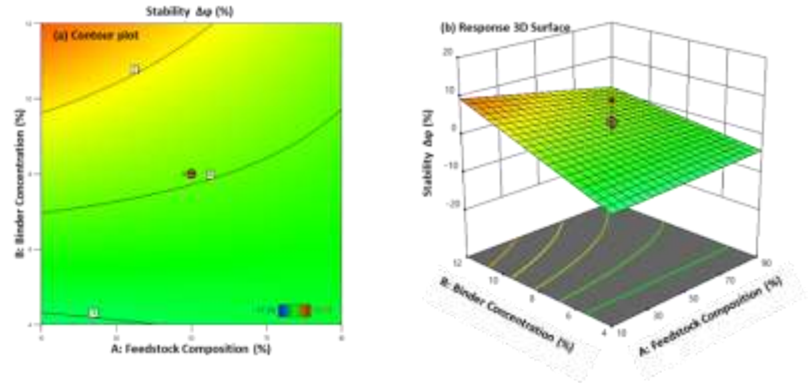

Fig. 37: Interaction plots of stability (Δϕ) for briquette samples

Modeled and Optimal Longitudinal Stability ΔL

The examination of the 2FI model yielded a significant result (F-value of 3.27 and a p-value of 0.0127) indicating the variables B, D, AC, and BD were significant ($p < 0.05$). The lack of Fit (F-value = 0.78) did not show statistical significance compared to the pure error (p-value = 0.6712). This is desirable as it signifies a good alignment between the model and the data. The fit statistics showed a high R^2 value (0.9878), implying that 98.78 % of the variation in the response variable can be explained. The adjusted R^2 and predicted R^2 are 0.8956 and 0.887, respectively, suggesting satisfactory agreement between the predicted and observed values. The precision ratio of 32.44 > 4 indicates a satisfactory signal-to-noise ratio.

$$\Delta L_b = -0.73 - 0.33\,\mathrm{A} + 2.16\,\mathrm{B} - 0.5\,\mathrm{C} - 2.21\,\mathrm{D} - 0.23\,\mathrm{AB} - 2.5\,\mathrm{AC} + 1.33\,\mathrm{AD} + 0.36\,\mathrm{BC} + 2.83\,\mathrm{BD} + 1.06\,\mathrm{CD} \tag{33}$$

Each coefficient of the model (**Eq. 33**) represents the effect of the corresponding factor on ΔL Positive coefficients indicate an increase in stability, while negative coefficients indicate a decrease. The positive coefficient for B, AD, BD, and CD suggests that increasing these factors positively affects ΔL. The interaction between the particle size, binder concentration, DP, and feedstock compositions resulted in an optimal ΔL of 3 %. **Fig. 38** shows the impact of combining two independent variables on the ΔL using the contour and 3D-surface plots.

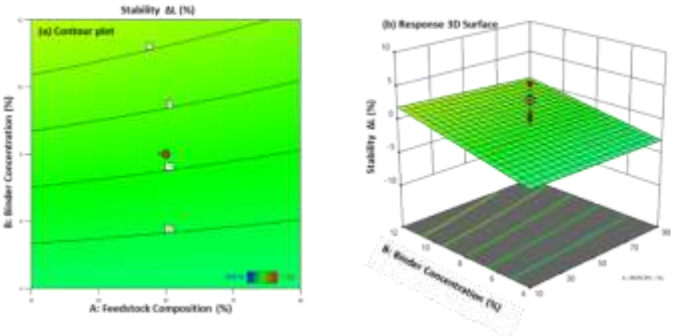

Fig. 38: Interaction plots of stability (ΔL) for briquette samples

Modeled and Optimal Shatter Indices (SI)

The quadratic model used in the ANOVA test for the SI yielded a statistically significant result, result, with an F-value of 105.05 and a $p < 0.0001$. The main factors are the composition of the A, B, C, Interaction (AC, BC), C^2, and D^2. These factors presented in **Table 28** are statistically significant, as indicated by p-values below 0.05. The absence of considerable variance in comparison to the inherent variability is suitable for model fitting. The high values of R^2 (0.9899), modified R^2 (0.9805) and predicted R^2 (0.9591) indicate that the model accurately explains a significant portion of the variation in the data. The precision value of 37.42 implies a signal-to-noise ratio, which shows that the model can effectively navigate the design space. The analysis validates the robustness of the model (**Eq. 34**) and its ability to effectively predict the SI based on these factors considered. The coefficients represent the impact of each factor on the SI.

$$\begin{aligned} SI_b = {} & 110.75 + 0.33\,\mathrm{A} + 0.63\,\mathrm{B} + 0.52\,\mathrm{C} + 1.88\,\mathrm{D} - 6.68\,\mathrm{AB} - 1.21\,\mathrm{AC} + 4.16\,\mathrm{AD} \\ & - 0.38\,\mathrm{BC} - 5.01\,\mathrm{BD} - 2.52\,\mathrm{CD} - 6.44\,\mathrm{A}^2 + 0.49\,\mathrm{B}^2 - 1.11\,\mathrm{C}^2 \\ & - 1.65\,\mathrm{D}^2 \qquad (34) \end{aligned}$$

The SI was optimized by considering variables such as particle size, binder concentration, DP, and feedstock compositions, resulting in a value of 110.7 %. **Fig. 39** demonstrates the impact of combining two independent variables on the shatter indices through the contour and 3D-surface plots.

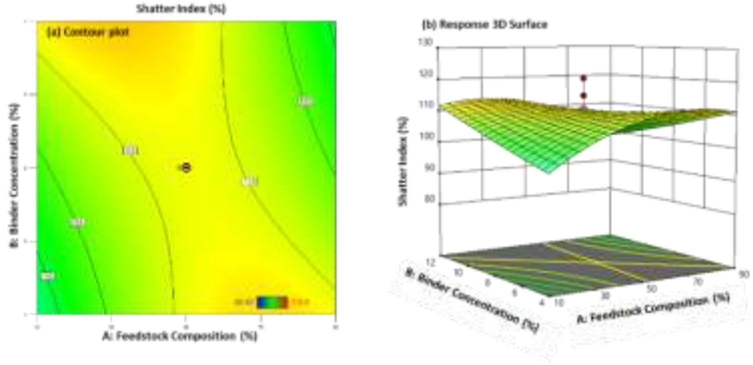

Fig. 39: Interaction plots of shatter indices for briquette samples

Modeled and Optimal Compressive Strength (CS)

A significant relationship is demonstrated by the analysis of variance (ANOVA) for the quadratic CS model, with an F-value of 6.29 and a p-value of 0.0005. This indicates that the model effectively explains a significant portion of the variance in CS. The statistically significant factors (p-values < 0.05) are D, B, the interaction between densification pressure and particle size (AC), the interaction between binder and particle size (BD), binder concentration squared (A^2), and particle size squared (D^2). The high p-value of 0.46 indicates that the lack of fit is not significant, implying that the model fits the data well. The R^2 of 0.8978 suggests that the model accounts for 89.78 % of the variability in CS. The adjusted R^2 value (0.8886) indicates that the model fits the data and is reliable. The R^2 of 0.8171 suggests that the model has a good level of accuracy for future observations. Moreover, the precision value of 22.57 indicates that the signal-to-noise ratio is sufficient for generating predictions; therefore, the model (**Eq. 35**) can effectively navigate the design space for CS.

$$CS_b = 8.32 - 0.36\,\mathrm{A} + 2.56\,\mathrm{B} - 0.81\,\mathrm{C} - 1.68\,\mathrm{D} + 0.5\,\mathrm{AB} - 1.73\,\mathrm{AC} + 0.24\,\mathrm{AD} - 0.43\,\mathrm{BC} + 2.59\,\mathrm{BD} + 1.19\,\mathrm{CD} - 2.20\,\mathrm{A}^2 - 1.65\,\mathrm{B}^2 - 0.58\,\mathrm{C}^2 - 0.55\,\mathrm{D}^2 \qquad (35)$$

The positive coefficients show that there is a direct relationship between an increase in the factor of interest and an increase in CS. On the other hand, the negative coefficients suggest that an increase in the corresponding factor leads to a decrease in CS. For example, the presence of a positive coefficient for B signifies that an increase in binder concentration leads to a corresponding increase in CS. The maximum CS of 8.62 kN/m² was achieved using particle size, binder concentrations, DP, and feedstock compositions. **Fig. 40** displays the impact of combining two separate factors on CS using contour and 3D-surface graphs.

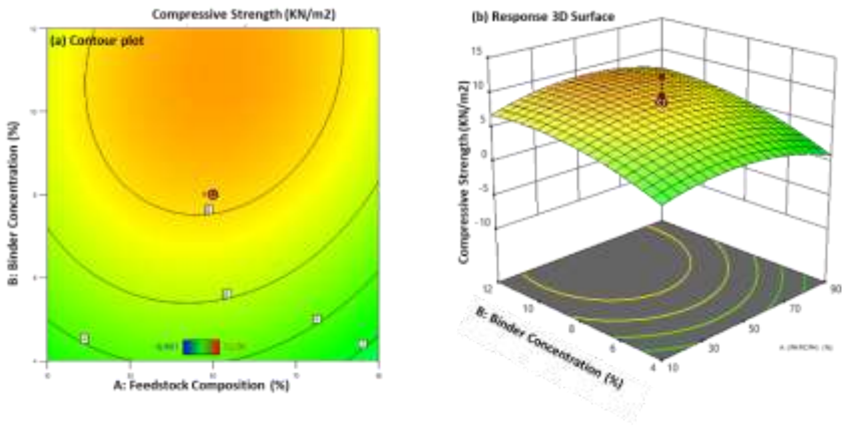

Fig. 40: Interaction plots of compressive strength for briquette samples

Table 28: ANOVA Results for Mechanical Analyses Optimization

Source	CD		RD		RR		TR		WR		$\Delta\phi$		ΔL		SI		CS	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Model	17.77	< 0.0001	7.30	0.00	12.62	< 0.0001	12.07	< 0.0001	22.83	< 0.0001	11.80	< 0.0001	3.27	0.01	105.05	< 0.0001	6.29	0.00
A-PAP: CPH	20.99	0.00	1.42	0.25	16.37	0.00	19.20	0.00	0.17	0.69	5.16	0.04	0.16	0.69	1050.06	< 0.0001	0.45	0.51
B-Binder	1.58	0.23	20.81	0.00	75.56	< 0.0001	72.52	< 0.0001	0.23	0.64	55.05	< 0.0001	7.10	0.02	160.02	< 0.0001	22.57	0.00
C-Densification Pressure	12.54	0.00	1.77	0.20	0.19	0.67	0.01	0.91	0.03	0.86	1.82	0.19	0.38	0.55	119.97	< 0.0001	2.27	0.15
D-Particle Size	9.32	0.01	13.57	0.00	1.43	0.25	3.48	0.08	0.44	0.52	13.65	0.00	7.44	0.01	0.01	0.91	9.72	0.01
AB	15.05	0.00	36.85	< 0.0001	0.02	0.90	15.73	0.00	68.67	< 0.0001	7.58	0.01	0.05	0.82	0.13	0.72	0.58	0.46
AC	53.50	< 0.0001	1.60	0.23	0.07	0.79	12.16	0.00	31.37	< 0.0001	5.10	0.04	6.34	0.02	77.61	< 0.0001	6.90	0.02
AD	6.40	0.02	5.96	0.03	0.04	0.84	2.80	0.12	4.29	0.06	0.22	0.64	1.79	0.20	0.97	0.34	0.13	0.72
BC	0.18	0.68	0.05	0.83	10.09	0.01	1.06	0.32	2.19	0.16	5.21	0.03	0.13	0.72	12.44	0.00	0.42	0.53
BD	0.72	0.41	5.81	0.03	0.40	0.54	1.21	0.29	22.75	0.00	6.27	0.02	8.15	0.01	0.12	0.73	15.45	0.00
CD	21.74	0.00	0.53	0.48	6.80	0.02	23.49	0.00	0.42	0.53	17.96	0.00	1.15	0.30	1.69	0.21	3.23	0.09
A^2	48.11	< 0.0001	0.53	0.48	20.83	0.00	6.11	0.03	167.44	< 0.0001	0.00	0.00	0.00	0.00	1.28	0.28	19.08	0.00
B^2	0.68	0.42	3.58	0.08	1.33	0.27	8.00	0.01	1.44	0.25	0.00	0.00	0.00	0.00	2.07	0.17	10.68	0.01
C^2	1.69	0.21	9.76	0.01	15.41	0.00	0.02	0.90	0.88	0.36	0.00	0.00	0.00	0.00	31.98	< 0.0001	1.33	0.27
D^2	71.77	< 0.0001	0.42	0.53	19.57	0.00	2.24	0.16	1.44	0.25	0.00	0.00	0.00	0.00	6.71	0.02	1.19	0.29

Modeled and Optimal Burning Rate (BR)

The ANOVA analysis for a quadratic model of BR indicates significance with a model F-value of 4.64 and a very low probability (0.28 %) of occurring due to noise. The BR is significantly influenced by the binder concentration (B), binder squared (B^2), and particle size squared (D^2). The model and data exhibit a satisfactory fit, as the lack of fit is not significant (p-value > 0.05). Further validation of the model's robustness is provided by its fit statistics, including R^2 (0.6372), adjusted R^2 (0.6240), and precision (18.85). The quadratic model (**Eq. 36**) effectively captures the relationship between the factors and the BR, providing valuable insights for design optimization. The relative impact of the factors is denoted by the coefficients, with higher absolute values suggesting greater influence.

$$\begin{aligned} BR_b = {} & -0.37 + 0.81\,\mathrm{A} - 2.63\,\mathrm{B} - 0.55\,\mathrm{C} - 0.89\,\mathrm{D} + 0.67\,\mathrm{AB} - 0.1\,\mathrm{AC} - 0.39\,\mathrm{AD} \\ & - 1.06\,\mathrm{BC} + 0.66\,\mathrm{BD} - 1.05\mathrm{CD} + 0.16\,\mathrm{A}^2 - 2.28\,\mathrm{B}^2 + 0.0063\,\mathrm{C}^2 \\ & - 1.44\,\mathrm{D}^2 \qquad (36) \end{aligned}$$

The optimal BR of 0.35 g/min was achieved through the interaction of particle size, binder concentration, DP, and feedstock compositions. The contour and 3D-surface graphs in **Fig. 41** highlight the effect of combining two independent variables on the BR.

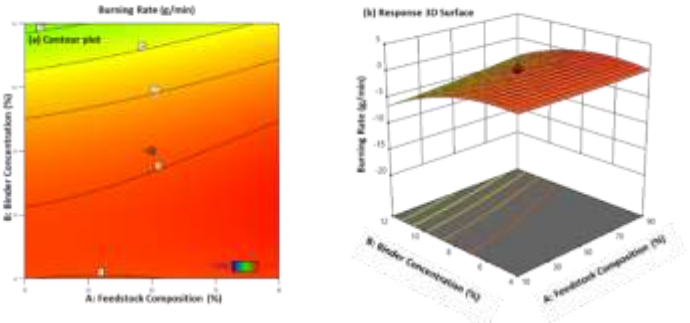

Fig. 41: Interaction plots of burning rate for briquette samples

Modeled and Optimal Ignition Time (IT)

The results indicate a significant model for IT, with an F-value of 33.41 ($p < 0.0001$). This implies that the model (**Eq. 37**) explains a substantial portion of the variation in IT. Key factors affecting ignition time are B and C. Simultaneously, IT is significantly influenced by the A and C. The model does not precisely fit the data, as evidenced by the significant lack of fit (F-value = 4.88, $p = 0.0434$). However, the R^2 value (0.8424) and adjusted R^2 (0.8172) show that the model explains a significant portion of the variance in IT. The model's predictive reliability is demonstrated by the reasonable agreement between the adjusted R^2 (0.8172) and predicted R^2 (0.7577). The model's effective navigation of the design space and a robust signal-to-noise ratio are both indicated by its adequate precision (21.8), which transcends the threshold of 4.

$$IT_b = 1.94 - 0.4414A - 7.37B - 0.9424C - 2.39D \quad (37)$$

The optimal IT of 2.75 min was achieved through the interaction of particulate size, binder concentration, DP, and feedstock composition. The contour and 3D-surface graphs in **Fig. 42** highlight the effect of combining two independent variables on IT.

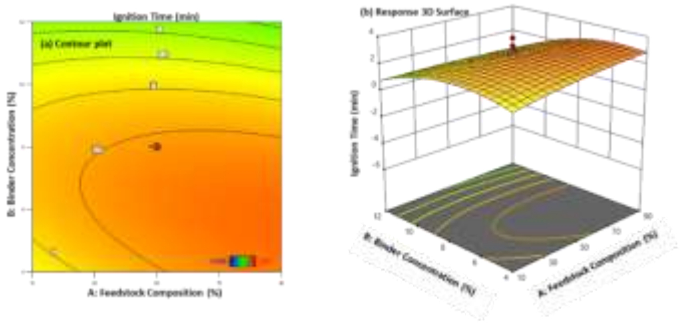

Fig. 42: Interaction plots of ignition time for briquette samples

Modeled and Optimal Specific Fuel Consumption (SFC)

The results suggest that the two-factor interaction (2FI) for SFC is highly significant (p-value = 0.0003) (**Table 29**) and accounts for a significant portion of the variation in SFC. The B, C, and AC (interaction between feedstock composition and densification pressure) have p-values less than 0.05, implying they are significant factors to the mode. However, the p-values for A, D, and interactions (AB, AD, BC, BD, and CD) are all greater than 0.05, indicating that they are not significant. The model adequately correlates with the data, as evidenced by the fact that the lack of fit is not significant (F-value = 3.31 and p-value of 0.0962). The model explains 79.83 % of the variability in SFC, as indicated by the R^2 (0.7983). The predicted R^2 value of 0.6470 closely aligns with the adjusted R^2 of 0.6922, suggesting the model is reliable in predicting SFC. The model's (**Eq. 38**) applicability in navigating the design space is supported by the adequate precision ratio of 12.55, which indicates an adequate signal-to-noise ratio.

$$SFC_b = 1.05 + 0.15A - 1.11B + 0.524C - 0.3460D + 0.071AB - 1.17AC + 0.28AD + 0.0085BC + 0.26BD + 0.026CD \quad (38)$$

The optimal SFC was determined to be 0.26 g/l when the particle size, binder concentration, DP, and feedstock composition were all calculated. The contour and 3D surface in **Fig. 43** demonstrate the effect of combining two independent variables on SFC.

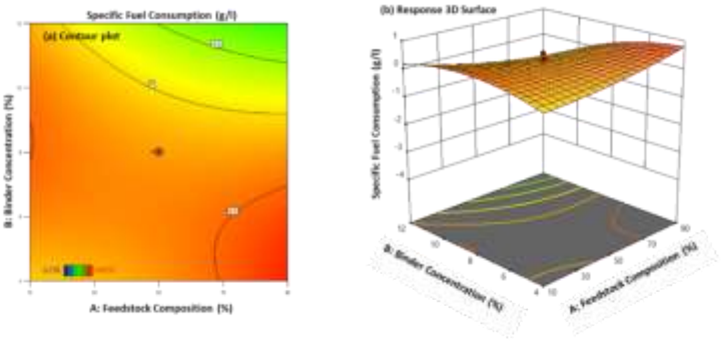

Fig. 43: Interaction plots of specific fuel consumption for briquette samples

Modeled and Optimal Heating Value (HV)

The ANOVA for a quadratic model that analyzed the HV demonstrated significance (F-value = 7.97 and p-value = 0.0001). This implies the model (**Eq. 39**) can predict the heating value. The A, B, AB, AC, A^2, and D^2 were all significant (p-value < 0.05). Simultaneously, the densification pressure (C), particle size (D), AD, BC, BD, CD, B², and C² are not significant (p-value > 0.1). This suggests that the model is well-suited to the data, as the absence of fit was not statistically significant (F-value = 1.37 and p-value = 0.3824). The fit statistics indicated a high R² (0.9598), and the adjusted R² (0.9386) indicated an excellent fit. The predicted R² (0.8674) is close to the adjusted R², suggesting the model's predictability is reliable. An adequate precision ratio (23.33) exceeding 4 signifies a sufficient signal. The model can be used to understand the relative impact of each independent variable (particle size, binder concentration, DP, and feedstock composition) on the heating value.

$$\begin{aligned} HV_b = 20.26 &- 4.49\,\mathrm{A} - 3.65\,\mathrm{B} - 0.84\mathrm{C} - 1.2\,\mathrm{D} + 4.46\,\mathrm{AB} - 3.13\,\mathrm{AC} + 0.43\,\mathrm{AD} \\ &- 0.53\,\mathrm{BC} - 1.22\,\mathrm{BD} + 0.95\,\mathrm{CD} - 1.74\,\mathrm{A}^2 + 0.38\,\mathrm{B}^2 - 0.76\,\mathrm{C}^2 \\ &- 1.94\,\mathrm{D}^2 \end{aligned} \tag{39}$$

When the particle size, binder concentration, DP, and feedstock composition were all considered, the optimal HV was determined to be 22.98 MJ/kg. The contour and 3D-surface graphs in **Fig. 44** demonstrate the effect of combining two independent variables on the HV.

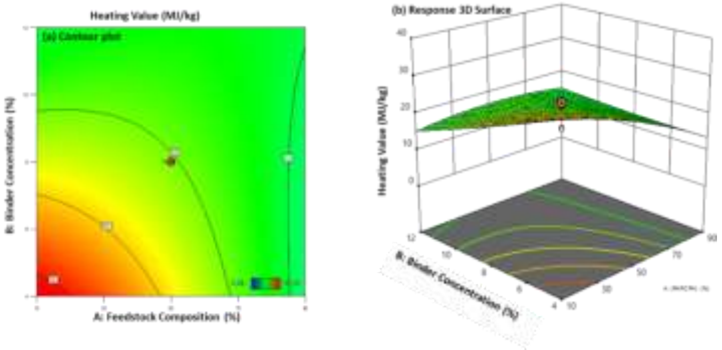

Fig. 44: Interaction plots of heating value for briquette samples

Table 29: ANOVA Results for Combustion Performance Analyses Optimization

Source	BR		IT		SFC		HV	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Model	4.64	0.0028	33.41	< 0.0001	7.52	< 0.0001	7.97	0.0001
A-PAP: CPH	3.18	0.0946	0.4257	0.5201	0.6395	0.4338	34.58	< 0.0001
B-Binder	20.78	0.0004	118.85	< 0.0001	34.82	< 0.0001	22.77	0.0002
C-Densification Pressure	0.2328	0.6364	1.94	0.1758	7.61	0.0125	1.21	0.2892
D-Particle Size	2.97	0.1056	12.43	0.0017	3.4	0.0807	2.45	0.138
AB	1.02	0.3277	0.00	0.00	0.0947	0.7616	22.76	0.0002
AC	0.0837	0.7763	0.00	0.00	25.88	< 0.0001	11.22	0.0044
AD	0.0982	0.7583	0.00	0.00	1.5	0.2352	0.2128	0.6512
BC	3.11	0.0984	0.00	0.00	0.0014	0.9708	0.3242	0.5775
BD	1.61	0.2243	0.00	0.00	1.24	0.2797	1.69	0.213
CD	3.07	0.1002	0.00	0.00	0.0132	0.9096	1.02	0.3277
A^2	0.1621	0.6929	0.00	0.00	0.00	0.00	5.9	0.0281
B^2	19.4	0.0005	0.00	0.00	0.00	0.00	0.2751	0.6076
C^2	0.9202	0.3526	0.00	0.00	0.00	0.00	1.12	0.3068
D^2	11.05	0.0046	0.00	0.00	0.00	0.00	7.4	0.0158

6.4 Conclusions and Recommendations

The hybrid composition of *Prosopis africana* pod (PAP) and cowpea husk (CPH) with cassava starch binder (CSB) was evaluated in terms of particle sizes, composition, binder concentrations, and DP. The proximate results, mechanical handling, and combustion properties of the briquettes were observed to exhibit varying differences. The optimization started with the modification of particle size, while the composition (50:50), binder concentration (10 %), and DP (34.5 KN/m^2) were kept constant. The results indicated that the properties were most suitable for smaller particles (150 µm) and were then used to evaluate the other independent variables. The effect of the composition was investigated by keeping the binder (10 %) and DP (34.5 KN/m^2) constant; the result showed that the briquettes with 50 % PAP composition were more favorable for heating and cooking. The third test was conducted to evaluate the impact of the binder. The DP was maintained at 34.5 KN/m^2, the PAP content at 50 %, and the particle size at 150 µm. According to the findings, briquettes with a higher binder concentration (12 %) were more suitable for mechanical handling, such as transporting, preserving, and packaging. Furthermore, the impact of DP was determined under these conditions, and the result showed that the briquette properties were enhanced by applying a higher DP. The RSM showed the optimal values for the briquette properties and models to improve the efficiency and effectiveness of the briquetting process. It also identified the most effective methods for utilizing the selected independent variables to convert biomass into solid biofuels and contribute to renewable energy advancement. Additional investigation is currently being conducted on the socio-techno-economic dimensions to facilitate the scaling of production, adoption, and business models to assure widespread utilization in rural and peri-urban areas of Nigeria and Africa.

Table 30: Experimental Results of the Proximate, Mechanical, and Combustion Analysis

Analyses	**Biomass Properties**	**Particle Size (µm)**				**Feedstock Composition (PAP: CPH) (%)**					**Binder (%)**				**Densification Pressure (KN/m^2)**		
		2360	**1000**	**425**	**150**	**(90:10)**	**(70:30)**	**(50:50)**	**(30:70)**	**(10:90)**	**12**	**10**	**6**	**4**	**34.5**	**68.95**	**103.42**
Proximate Analyses	Moisture Content (%)	27.00	25.00	22.00	18.00	28.00	36.00	18.00	36.00	33.00	12.10	18.00	22.00	23.00	10.00	18.00	21.00
	Volatile Matter (VM) Content (%)	69.80	73.70	76.60	77.50	66.90	60.00	77.50	59.00	60.80	79.00	77.50	71.20	70.00	77.20	77.50	78.00
	Ash Content (%)	1.14	1.09	1.10	1.09	4.20	3.30	1.09	3.50	2.90	1.12	1.09	1.02	1.10	1.10	1.09	0.99
	Fixed Carbon (FC) Content (%)	2.06	0.21	0.30	3.41	0.90	0.70	3.41	1.50	3.30	7.78	3.41	5.78	5.90	11.70	3.41	0.01
Mechanical (Handling) Analyses	Compressed Density, CD (kg/m^3)	0.73	0.96	1.05	1.24	1.20	1.16	1.24	1.07	1.01	1.82	1.24	0.89	0.72	1.34	1.24	1.02
	Relaxed Density, RD (kg/m^3)	0.50	0.68	0.79	0.93	1.15	1.04	0.93	0.85	0.81	1.68	0.93	0.42	0.33	0.89	0.93	1.29
	Relaxation Ratio, CD/RD (-)	1.48	1.43	1.34	1.34	1.05	1.12	1.34	1.26	1.26	1.08	1.34	2.12	2.18	1.51	1.34	0.79
	Durability/Tumbling resistance, TR (%)	0.823	0.884	0.886	0.910	0.826	0.885	8.863	0.823	0.844	0.956	0.910	0.932	0.898	0.98	0.91	0.87
	Water Resistance, WR (%)	26.60	36.40	52.04	89.56	93.15	88.58	89.56	79.30	89.59	95.45	89.56	92.01	89.56	92.11	92.03	89.56
	Stability (% Δϕ)	2.01	1.76	3.36	3.41	3.55	2.79	3.41	3.01	3.67	3.10	3.41	2.81	2.75	0.76	0.79	3.41
	Stability (% ΔL)	-18.13	-8.09	-5.85	-13.59	3.44	1.94	-13.59	-3.85	-4.02	1.92	-13.59	0.89	-3.21	0.45	0.80	-13.59
	Shatter Index	0.88	0.94	0.96	0.96	0.9645	0.9672	0.9694	0.9652	0.9668	0.954	0.96	0.921	0.897	0.982	0.980	0.960
	Compressive Strength (kN/m^2)	3.775	7.129	7.128	7.129	7.129	7.079	7.129	5.851	7.128	7.112	7.129	6.992	6.910	7.212	7.129	7.106
Combustion Performance Evaluation	Burning Rate (g/min)	1.013	0.585	0.519	0.514	0.482	0.526	0.514	0.440	0.560	0.590	0.581	0.610	0.693	0.510	0.581	0.481
	Ignition Time (mins)	1.50	1.95	2.00	2.77	3.25	2.88	2.77	2.53	2.20	2.85	2.77	1.60	1.20	2.79	2.77	2.00
	Specific Fuel Consumption (g/l)	0.316	0.298	0.297	0.235	0.217	0.257	0.235	0.227	0.242	0.562	0.470	0.433	0.390	0.432	0.470	0.501
	Heating Value (MJ/kg)	12.65	12.66	13.19	14.45	11.75	10.50	14.45	10.61	11.55	16.25	14.45	14.21	14.05	17.33	14.45	13.33

CHAPTER SEVEN

CONCLUSIONS, SUGGESTIONS FOR FUTURE WORK AND CONTRIBUTIONS TO KNOWLDEGE

7.1 Conclusions

In this dissertation, we conducted a comprehensive evaluation of the bioenergy potential of agricultural biomass residues in Africa, emphasizing the application of circular economy principles to promote sustainable energy solutions. This research specifically focused on residues classified as technical potential, meaning they are unlikely to compete with other uses. Additionally, we explored the valorization of *Prosopis africana* biomass for bioenergy applications.

Our findings reveal that agricultural residues in Africa hold significant promise for bioenergy production. The analysis demonstrated that these residues could be efficiently converted into bioenergy, offering a viable solution to the continent's severe energy poverty while contributing to environmental sustainability. By utilizing empirical data analysis and advanced modeling techniques, we quantified the energy potential of various crop residues, thereby providing a robust foundation for integrating these resources into Africa's energy mix.

In parallel, the investigation on *Prosopis africana* biomass revealed its substantial bioenergy potential. The characterization of *Prosopis africana* wood, barks, leaves, and pods indicated favorable physical, thermal, and chemical properties for biofuel production. Despite certain limitations in its use as a standalone feedstock for large-scale biofuel production, *Prosopis africana* biomass shows considerable promise when combined with other biomass sources to create hybrid biofuels. This approach not only enhances the overall feedstock availability but also leverages the unique properties of *Prosopis africana* to optimize biofuel production processes. Moreover, the optimization of briquettes composed of *Prosopis africana* pods and cowpea husks, bound with cassava starch, demonstrated that optimal particle size, binder concentration, and density pressure significantly improve mechanical handling and combustion properties. These optimized briquettes exhibit potential for practical applications in heating and cooking, particularly in rural and peri-urban areas, thereby addressing energy access issues and contributing to the socio-economic development of these regions.

This research underscores the feasibility and viability of utilizing agricultural residues and *Prosopis africana* biomass for bioenergy production in Africa. The integration of these bioenergy resources can mitigate energy poverty, support economic development, and promote environmental sustainability. Future research should focus on the socio-techno-economic dimensions of bioenergy production, adoption, and business models to ensure the widespread implementation and success of bioenergy initiatives across Africa.

7.2 Implications of Biomass Analysis

This research has profound implications for advancing the field of bioenergy within the context of Africa's unique energy landscape. Over 600 million Africans lack access to electricity, and approximately 900 million do not have clean cooking facilities. This highlights the urgent need to evaluate Africa's accessible biomass residues for bioenergy production. This study is particularly timely, given the increasing global population and the corresponding rise in energy demand. The shift towards environmentally friendly fuels is critical for mitigating environmental degradation and climate change. Sustainable bioenergy production can help protect cultivable land and forests from desertification, excessive flooding, and unpredictable temperature fluctuations. Evaluating biomass residues allows us to determine the available resources and how to effectively valorize them for energy production, thereby addressing the continent's energy poverty. This study suggests implementing further incentives, tax reductions, and comprehensive policy and regulatory frameworks to support bioenergy development. Improved farm practices and advanced technologies are essential to reduce waste and enhance conversion processes, producing bioenergy that is equivalent to fossil fuels in terms of quality and efficiency. The role of stakeholders is crucial, ranging from research and technological advancements in biomass projects to governmental policymaking that benefits communities and regulates industrial systems to ensure the production of high-quality bioenergy products. These efforts will ensure that such products are accessible to the public at reasonable prices and competitive in global markets. Implementing regulations that promote the proper use of residues can facilitate the transition to a circular bioeconomy, boosting the country's economic resilience. However, the study revealed that the quantity of recoverable biomass residues is relatively low, complicating sustainable biofuel production due to crop seasonality. Ensuring a steady supply of feedstock that meets the compositional standards for biofuel production is crucial for both household and industrial use. Beyond identifying new potential feedstocks, comprehensive characterization is essential for efficient biofuel production.

7.3 Suggestion for Future Work

The study has significantly contributed to understanding the bioenergy potential of biomass residues in Nigeria and Africa, specifically focusing on Prosopis africana biomass, which is also cultivated in Asia, Southern, and North America. The experiments conducted on *Prosopis africana* biomass waste provided valuable insights into various value-added approaches for producing biofuels. However, further investigations are necessary to fully realize the potential of this biomass source. The following challenges and future research directions are proposed:

1. Evaluation of Pyrolysis Temperature on Physicochemical Characteristics of Biochar to understand the optimal pyrolysis conditions for maximizing the quality and yield of biochar from *Prosopis africana* biomass and investigate the effect of varying pyrolysis temperatures on the physicochemical properties of biochar produced from *Prosopis africana* biomass wastes.

2. Enzymatic Hydrolysis of Pretreated *Prosopis Africana* Biomass to enhance the efficiency of glucose production through the enzymatic hydrolysis of pretreated *Prosopis africana* biomass and evaluate the effectiveness of various pretreatment methods followed by enzymatic hydrolysis to maximize glucose yield from *Prosopis africana* biomass wastes.

3. Socio-Economic, Risk, and Environmental Impact Assessment to evaluate the broader implications of deploying and scaling the use of *Prosopis africana* biomass for bioenergy production in Africa. This will require conducting a comprehensive assessment of the socio-economic benefits, potential risks, and environmental impacts associated with the large-scale utilization of *Prosopis africana* biomass in Africa.
4. Repeating this study for other agro waste and biomass of Nigerian origin.

7.4 Contributions to Knowledge

The research highlights the potential of Prosopis africana as a sustainable feedstock for biofuel production, addressing energy poverty and contributing to GHGs emissions reductions in Africa. The study provides an extensive analysis of various agricultural residues, particularly emphasizing the energy potential of crops and unconventional biomass sources like Prosopis africana, demonstrating their viability for renewable energy applications. The findings advocate circular economy principles by promoting the recycling of agricultural waste into valuable energy resources. This approach not only addresses energy challenges but also fosters environmental sustainability through effective waste management practices. The research explores the optimization of briquette production using a hybrid composition of Prosopis africana pods and cowpea husks. It identifies optimal conditions for producing high-quality briquettes, which can enhance mechanical handling and combustion properties, thereby improving the efficiency of biomass utilization for energy

List of Publications

Chidiebele Uzoagba, Peter A. Onwualu, Edmund Okoroigwe, Marzieh Kadivar, William S. Oribu, Nonhlanhla G. Mguni, Vitalis C. Anye, Abdulhakeem Bello, Michael C. Mozie, Michael Aperebo, Ibukunoluwa A. Adedeji (2024). *A Review of Biomass Valorization for Bioenergy and Rural Electricity Generation in Nigeria.* Cureus Journal of Engineering (SpringerNature). https://www.cureusjournals.com/publish/articles/65-a-review-of-biomass-valorization-for-bioenergy-and-rural-electricity-generation-in-nigeria/preview#!/

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