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Biomass Briquettes for Sustainable Households and Climate Resilience in Nigeria

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Abstract

This study explores biomass briquette production in energy planning for sustainable household utilization and climate resilience in Bauchi State, Nigeria. Adopting a mixed-methods research design, the study combines quantitative and qualitative tools, including structured household surveys (n=300), semi-structured interviews with key stakeholders (n=20), focus group discussions, and laboratory tests on briquette samples to evaluate the feasibility and potential impact of biomass briquettes as an alternative energy source. The research assessed key factors, including biomass feedstock availability, community acceptance, and the technical, economic, and environmental viability of briquette production. Stakeholder mapping identified five categories: end-users, producers, feedstock suppliers, policymakers, and intermediaries, and a multi-stage sampling method ensured comprehensive representation. Findings reveal that biomass resources are widely available across the study areas, with sawdust, rice husk, and groundnut shells being the primary feedstocks. Laboratory tests demonstrated that sawdust-based briquettes offered the highest calorific value and combustion efficiency, outperforming traditional fuels such as firewood. The potential for biomass briquette production to reduce energy costs was widely recognized, as respondents identified several barriers to adoption, including lack of awareness, high initial costs, and inadequate infrastructure for production. The awareness of biomass briquettes was moderately high, while adoption readiness varied, with 75% of respondents indicating a willingness to adopt if the fuel was affordable. This research emphasizes the need for targeted policy interventions and public education campaigns to address awareness gaps and build capacity for briquette production. By integrating biomass briquette production into Nigeria's energy planning, this enhances climate resilience and promotes sustainable energy transitions in urban and rural households. The results provide actionable insights for policymakers, energy planners, and environmental advocates seeking to incorporate alternative energy solutions into Nigeria's broader energy strategy.

Keywords: Biomass Briquettes, Sustainable Household Energy, Urban Energy Planning, Climate Resilience, Renewable Energy.

1.0 Introduction

Nigeria's rapid urbanization and population growth have intensified the demand for sustainable and resilient energy systems, especially in urban households. As the country grapples with severe energy poverty, affecting over 86 million people, and environmental degradation, integrating alternative energy sources like biomass briquettes into urban energy planning has become increasingly critical (NBS, 2022; FAO, 2022). Biomass briquettes, produced from agricultural and forestry residues, present a viable, low-carbon, renewable energy option that can contribute to sustainable household energy utilization and

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climate resilience (Ajimotokan et al., 2019; Ibitoye et al., 2023).

Biomass briquette technology offers several ecological and socio-economic advantages. It promotes waste-to-energy conversion and reduces greenhouse gas emissions. Briquette use also minimizes deforestation pressures caused by traditional firewood and charcoal usage (Njenga et al., 2019). Additionally, briquette use can improve indoor air quality and reduce health risks associated with biomass smoke (Akolgo et al., 2018). It can also provide income-generating opportunities through localized production (Mperejekumana et al., 2024). Nigeria's abundant agricultural and biomass residues further strengthen the case for leveraging briquette production, with studies showing high resource potentials across various regions (Jekayinfa et al., 2020; Okedu et al., 2024).

To maximize the benefits of biomass briquettes, it is imperative to mainstream their production and distribution into Nigeria's urban energy planning frameworks. This requires a systems-thinking approach that considers supply chain optimization, appropriate technology deployment, affordability, and supportive policy interventions (Ghatak & Mujumdar, 2018; Oginni et al., 2019). Recent advancements in densification technologies and process optimization have significantly improved briquette quality and efficiency (Adam et al., 2024; Nganko et al., 2024), making the technology more adaptable for urban energy needs.

Despite policy efforts like the National Renewable Energy Policy (2018) and the draft National Clean Cooking Policy (Federal Ministry of Environment, 2023), implementation gaps remain. Integrating biomass briquette systems into urban energy planning could bridge Nigeria's clean energy deficit and contribute to the broader goals of climate adaptation and sustainable development (Federal Republic of Nigeria, 2020; IPCC, 2021). It can also contribute to energy justice (IEA, 2022). This paper explores the potential and pathways for embedding biomass briquette production into urban energy strategies, targeting sustainable household energy access and urban climate resilience in Nigeria.

2.0 Literature Review

To frame the integration of biomass briquette production into energy planning in Nigeria, particularly for rural and semi-arid regions like Bauchi State, this literature review synthesizes

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key themes around renewable biomass resources, energy access, policy frameworks, technological viability, and climate resilience. The goal is to establish a conceptual and empirical foundation for the proposed study.

2.1 Biomass as a Renewable Energy Resource in Nigeria

Nigeria, grappling with significant energy challenges characterized by widespread energy poverty and a heavy reliance on traditional biomass fuels like firewood and charcoal (UNDP, 2020), faces severe consequences including deforestation, air pollution, and increased greenhouse gas emissions (Acheampong & Osei-Opoku, 2023). However, the nation is endowed with abundant renewable biomass resources that hold substantial potential for providing cleaner, more sustainable energy alternatives (Ibitoye et al., 2023). Notably, the utilization of biomass residues—such as sawdust, agricultural waste, and forestry by-products—for the production of briquettes presents a promising avenue to mitigate these challenges (Sharma et al., 2020; Ghatak & Mujumdar, 2018). These findings are particularly relevant for semi-arid and rural settings such as Bauchi State, where traditional energy use is prevalent and agricultural waste is readily available.

2.2 Biomass Briquette Production and Energy Access

Biomass briquettes, formed through the compaction of biomass materials, offer a practical solution for cooking and heating. Their potential to diminish dependence on conventional cooking fuels and provide cleaner energy options for households has garnered significant attention (Oladosu et al., 2023). In the Nigerian context, the adoption of biomass briquettes holds the promise of enhancing energy access, especially in rural communities where modern energy services remain scarce (Yunusa et al., 2024). Beyond addressing energy access, the use of briquettes contributes to climate resilience by lowering the emissions associated with traditional cooking practices (Njenga et al., 2019). The potential impact of improved energy access through briquettes is particularly significant in states like Bauchi, which have a large rural population relying on traditional fuels.

2.3 Energy Planning and Policy Framework

The successful integration of biomass briquette production into national energy planning necessitates supportive policies and well-defined strategies. The Nigerian government has demonstrated a commitment to promoting renewable energy through initiatives such as the

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National Renewable Energy Policy (2018) and the National Development Plan (2020), both underscoring the importance of sustainable energy solutions for national progress. However, the specific implementation of these policies concerning biomass briquettes remains underdeveloped.

The National Clean Cooking Policy Draft of 2023 represents a step towards addressing household cooking energy needs, identifying biomass briquettes as a crucial component of the solution (Federal Ministry of Environment, 2023). A comprehensive energy policy framework that explicitly incorporates biomass briquettes within the broader renewable energy landscape could significantly enhance household energy utilization while simultaneously advancing the nation's climate change mitigation objectives. For a state like Bauchi, where fuelwood scarcity and environmental degradation are growing concerns, the inclusion of briquettes in energy planning could offer a sustainable alternative, provided that regional-specific implementation strategies are developed.

2.4 Technological and Economic Aspects of Biomass Briquette Production

The efficient production of biomass briquettes relies on appropriate technologies and sufficient infrastructure. Numerous studies have investigated the critical parameters influencing briquette production efficiency, including the type of biomass feedstock, the applied compaction pressure, the binder material used, and the specific production techniques employed (Adam et al., 2024; Ossei-Bremang et al., 2024). Optimizing these parameters can substantially improve the calorific value and mechanical durability of the briquettes, thereby enhancing their suitability for domestic use (Vaneck Bot et al., 2022).

Research within Nigeria has identified abundant biomass resources suitable for briquette production, with agricultural residues such as groundnut shells, sawdust, and rice husks showing particular promise (Jekayinfa et al., 2020; Akhtar et al., 2024). Given Bauchi State's significant agricultural output, these findings highlight the potential for utilizing locally sourced agricultural waste for briquette production.

The economic viability of biomass briquette production in Nigeria is shaped by several key

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factors, including the cost of raw materials, the investment in production technologies, and the prevailing market demand. While the initial capital investment for briquette production facilities might be considerable, the long-term economic advantages, such as the creation of employment opportunities and the reduction in healthcare expenditures associated with traditional cooking methods, position it as a potentially sound investment (Gitau et al., 2019).

The possibility of scaling up biomass briquette production through localized, decentralized systems could enhance the accessibility of affordable energy solutions for households, especially in remote and off-grid areas (Sharma et al., 2024). Establishing small-scale briquette production enterprises in Bauchi's rural communities could not only provide clean energy but also stimulate local economic growth.

2.5 Climate Resilience and Environmental Benefits

Biomass briquettes contribute to climate resilience through multiple pathways. Primarily, by decreasing the reliance on firewood and charcoal, their use can play a crucial role in mitigating deforestation and land degradation, which are significant environmental challenges in Nigeria (Acheampong & Osei-Opoku, 2023). Secondly, the production and combustion of briquettes offer a lower-carbon alternative to traditional fuels, thereby contributing to the reduction of greenhouse gas emissions. Research indicates that the carbon footprint of biomass briquettes is lower than that of conventional cooking fuels (Oladosu et al., 2023; Ghatak & Mujumdar, 2018).

The adoption of briquettes for household energy will lead to a reduction in indoor air pollution, a major health concern in many Nigerian households that depend on traditional biomass fuels (Mperejekumana et al., 2024). For a state like Bauchi, where desertification and reliance on fuelwood are prevalent, the shift to briquettes offers a pathway towards greater environmental sustainability and improved public health. The promotion of biomass briquettes also aligns with global climate policies, such as the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). By integrating biomass briquette production into Nigeria’s energy planning, the country can contribute to global climate change mitigation efforts while

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simultaneously addressing domestic energy needs (Intergovernmental Panel on Climate Change, 2021). Therefore, a focused strategy to promote briquette adoption in regions like Bauchi can contribute to Nigeria's broader commitment to sustainable development and climate action.

3.0 Methodology

This study adopted a mixed-methods research design integrating both qualitative and quantitative approaches to assess the integration of biomass briquette production into urban energy planning for sustainable household utilization and climate resilience in Bauchi State, Nigeria. The research combined exploratory, descriptive, and experimental case study methods to comprehensively analyze the availability of biomass feedstock, community acceptance, and the technical, economic, and environmental viability of biomass briquettes.

Three towns representing the North (Azare), Central (Ningi), and South (Toro) senatorial districts of Bauchi State were purposively selected based on agro-ecological diversity and the availability of agricultural residues relevant for biomass briquette production (see Figure 1). This purposive selection ensured that the study captured variation in feedstock types and socio-economic contexts across the state. Within each selected town, a multi-stage sampling strategy was employed to ensure representative and inclusive stakeholder participation.

At the first stage, stratified sampling was used to divide stakeholders into five key strata: end-users (households), producers, feedstock suppliers, policymakers, and intermediaries. This ensured coverage of all critical actors along the biomass briquette value chain. Within each stra-tum, cluster sampling was used to identify physical locations or communities where target groups are concentrated.

From the identified clusters, purposive sampling was applied to select information-rich respondents, especially among producers, policymakers, and intermediaries, where expertise and involvement in briquette or energy planning were key criteria. Finally, random sampling was employed within the household (end-user) stratum, where structured questionnaires were administered to randomly selected households in each town cluster to minimize selection bias and enhance generalizability.

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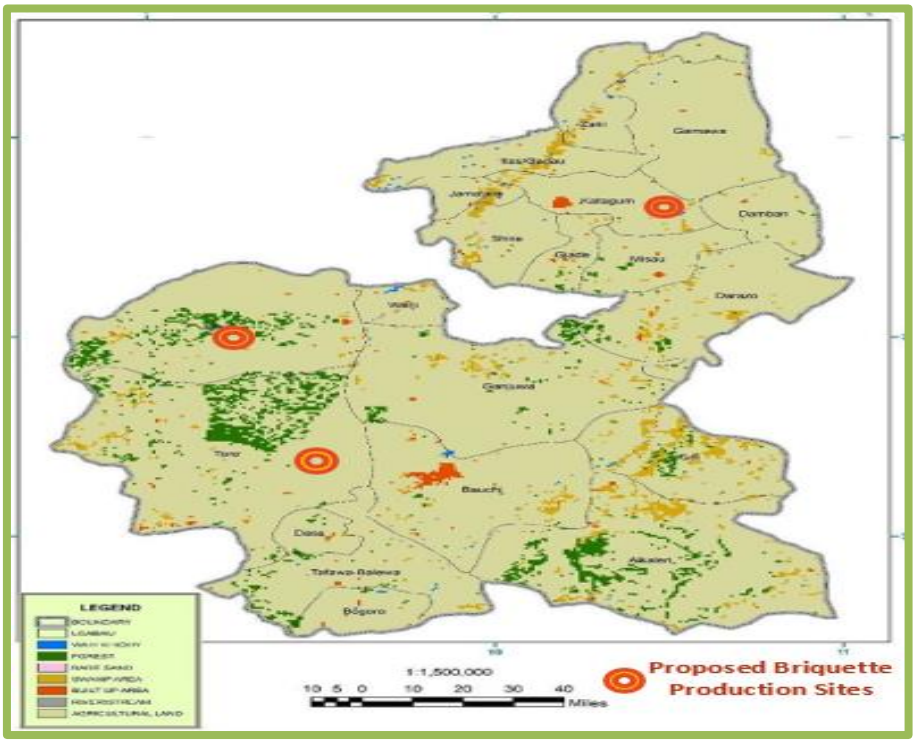


Figure 1: Land Use Map of Bauchi State Showing Briquettes Production Towns within Bauchi State
Source: Author's Compilations, 2024.

Data collection involved structured questionnaires administered to households and producers to gather information on energy practices, briquette perception, and adoption readiness. Semi-structured interviews targeted policymakers and market actors to explore regulatory and supply chain dynamics, while FGDs in each zone captured socio-cultural dimensions and com-munity feedback. Instruments were piloted and refined for validity.

Experimental laboratory tests assessed briquette quality and emissions using rice husk, sawdust, and groundnut shells with cassava starch as a binder. Combustion efficiency, calorific value, and emission metrics were measured using calorimeters, emission analyzers, and standard-ized ASTM/ISO protocols, with kerosene and firewood as control fuels.

Quantitative data were analyzed using SPSS for descriptive and inferential statistics, while

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qualitative data were thematically coded in NVivo, following triangulation to enhance result robustness. Findings were synthesized to evaluate briquette feasibility within Nigeria's energy policy framework, supporting climate-resilient urban energy transitions.

4.0 Data Analysis, Presentation, and Interpretation

4.1 Demographic Characteristics of Respondents

Table 1 summarizes the demographic information of respondents across three different locations: Azare, Ningi, and Toro, in Bauchi State. Azare had the highest male percentage (61.6%) while Toro had the highest female percentage (43.1%).The largest age group across all locations was between 26-35 years, especially in Toro (29.2%).The marital status of respondents is categorized into married, single, and divorced/widowed. Most respondents in all locations were married; with Azare having 50.7% married individuals. The majority had completed secondary education, with Azare showing 44% of respondents with secondary education.

The respondents' main occupations, including farming, entrepreneurship, civil service, and trade, were recorded. Farming was the most common occupation in all locations, with Azare showing 41.1% of respondents as farmers. In all locations, households of 4-5 members were the most common, particularly in Azare (36.4%).

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Table 1: Demographic Characteristics of Respondents

Characteristic	Azare (%)	Ningi (%)	Toro (%)	Total (%)
Gender				
Male	61.6	57.6	56.9	58.3
Female	38.4	42.4	43.1	41.7
Age Group				
18-25 years	27.4	28.2	25.0	26.9
26-35 years	24.7	28.2	29.2	26.9
36-45 years	18.8	16.5	18.1	17.8
46-55 years	15.1	15.3	14.5	14.9
56 years and above	14.0	11.8	13.2	13.4
Marital Status				
Married	50.7	55.3	57.5	53.0
Single	39.7	37.6	35.4	38.3
Divorced/Widowed	9.6	7.1	7.1	8.7
Education Level				
Primary School	23.3	28.2	26.4	26.1
Secondary School	44.0	42.4	43.1	43.5
Tertiary Education	23.3	21.2	22.2	22.2
No Formal Education	9.4	8.2	8.3	8.2
Occupation				
Farmer	41.1	40.0	40.3	40.4
Entrepreneur	22.0	23.5	22.2	23.0
Civil Servant	14.7	13.5	13.9	14.0
Trader	11.0	12.9	11.1	11.6
Student	5.5	7.1	6.9	6.5
Household Size				
1-3 members	30.1	35.3	37.8	34.5
4-5 members	36.4	33.5	33.3	37.8
6-10 members	28.7	26.4	25.0	27.8
Above 10 members	4.8	4.7	3.9	3.9

Source: Author's Fieldwork, 2024.

4.2 Monthly Income Distribution of Respondents

Table 2 categorizes respondents based on their monthly income, which is divided into different income ranges. The majority of respondents in all locations earned between ₦20,001 and ₦50,000, with Azare having 29.0% in this category. It shows a slightly higher income

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level for respondents in Ningi and Toro, with 30.6% and 27.0%, respectively, in the ₦50,001 - ₦100,000 range. This indicates varying economic levels among the communities.

Table 2: Monthly Income Distribution of Respondents

Monthly Income Range (₦)	Azare (%)	Ningi (%)	Toro (%)	Total (%)
≤ 20,000	18.6	22.4	21.0	20.7
20,001 - 50,000	29.0	28.2	30.6	29.1
50,001 - 100,000	23.2	26.5	27.0	25.5
100,001 - 150,000	18.6	13.5	14.5	15.4
150,001 and above	10.5	9.4	7.0	9.3

Source: Author's Fieldwork, 2024.

4.3 Monthly Spending on Cooking Fuel

Table 3 shows how much respondents spend on cooking fuel each month. Most respondents across all locations spend between ₦10,001 and ₦20,000 on cooking fuel each month (40.0% in Azare, 44.7% in Ningi, and 45.8% in Toro). However, a significant number of respondents spend less than ₦5,000 on fuel, particularly in Azare (9.6%).It's interesting to note that spending in the higher categories (₦20,001 and above) was lower in Azare compared to Ningi and Toro. This may reflect regional differences in fuel availability, costs, or preferences for alternative energy sources.

Table 3: Monthly Spending on Cooking Fuel

Monthly Spending on Fuel (₦)	Azare (%)	Ningi (%)	Toro (%)	Total (%)
≤ 5,000	9.6	8.2	6.3	7.8
5,001 - 10,000	16.5	18.8	19.4	18.1
10,001 - 20,000	40.0	44.7	45.8	43.9
20,001 - 30,000	17.8	15.3	15.3	16.2
30,001 and above	16.1	13.5	13.2	14.0

Source: Author's Fieldwork, 2024.

4.4 Perception of Biomass Briquette Production

Table 4 explores respondents' perceptions regarding biomass briquette production, with a focus on the viability and infrastructure related to it. Respondents generally agreed that biomass resources were available for production (mean scores ranging from 3.55 to 3.71). Azare had the highest agreement, indicating that this area

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might have more accessible resources for briquette production. The perception that biomass briquette production is economically viable received moderate agreement, with a mean score of 3.05 overall. Azare scored the lowest on this, which may suggest concerns about economic feasibility in this region. This statement had the lowest agreement across all locations, with the mean score ranging between 1.98 and 2.11. This suggests that respondents believe there is a lack of infrastructure for biomass briquette production, a critical barrier to widespread adoption. Respondents believed that biomass briquette production could reduce energy costs, as reflected in higher mean scores (around 3.5). This point to a positive view of biomass briquettes as a potential solution for energy challenges.

Table 4: Perception of Biomass Briquette Production

Statement	Azare (Mean Score)	Ningi (Mean Score)	Toro (Mean Score)	Total (Mean Score)
Availability of biomass resources	3.71	3.55	3.61	3.68
Biomass briquette production is economically viable	3.02	3.15	3.12	3.05
Infrastructure for biomass briquette production exists	2.11	1.98	2.03	2.05
Biomass briquette production can reduce energy costs	3.50	3.62	3.41	3.51

Source: Author's Fieldwork, 2024.

4.5 Biomass Feedstock Availability and Accessibility

Table 5 shows the relative abundance and accessibility of key biomass feed stocks across the three selected LGAs (Azare, Ningi, and Toro), within Bauchi State. Rice Husk is highly available in Azare due to the presence of rice mills but is less available in Toro, suggesting a geographic limitation in feedstock sourcing. Groundnut Shells are most available in Ningi, correlating with active groundnut farming in that region. Sawdust is consistently available in all three locations, indicating a stable supply from widespread sawmill operations, while Maize Stalks show moderate availability across all locations, suggesting it is a generally accessible but not dominant feedstock.

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Table 5: Biomass Feedstock Availability and Accessibility by Location

Biomass Feedstock	Azare (Availability)	Ningi (Availability)	Toro (Availability)	Primary Source
Rice Husk	High	Moderate	Low	Rice mills
Groundnut Shells	Moderate	High	Moderate	Groundnut farms
Sawdust	High	High	High	Sawmills
Maize Stalks	Moderate	Moderate	Moderate	Farms

Source: Author's Fieldwork, 2024.

4.6 Laboratory Analysis Results of Briquette Samples

Table 6 summarizes laboratory analyses that compare the physical and combustion properties of briquettes made from different feed stocks, all using cassava starch as a binder, in order to demonstrate the efficiency, cleanliness, and overall performance of biomass briquettes compared to firewood, providing scientific justification for their adoption. Sawdust-based briquettes perform the best, with the highest calorific value (19.8 MJ/kg), longest combustion time (52 minutes), and the lowest ash and smoke emissions. Rice husk briquettes also show good performance, especially in terms of low smoke emission. Groundnut shell briquettes lag slightly in energy value and smoke output but are still better than traditional firewood.

Table 6: Laboratory Test Results of Briquette Samples

Briquette Type (Feedstock + Binder)	Calorific Value (MJ/kg)	Combustion Time (mins)	Ash Content (%)	Smoke Emission Level	Comparison with Firewood
Rice Husk + Cassava Starch	18.5	45	4.5	Low	Better
Sawdust + Cassava Starch	19.8	52	3.2	Very Low	Much Better
Groundnut Shell + Cassava Starch	17.2	41	5.1	Moderate	Slightly Better

Source: Author's Fieldwork, 2024.

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4.7 Briquette Adoption Readiness and Awareness Level

Table 7 assesses the social dimension of the project, gauging how aware and prepared households are to transition to biomass briquettes, with the purpose of highlighting the behavioral and educational barriers and potentials for briquette adoption at the grassroots level. Awareness levels are moderately high (66% have heard of briquettes).Nearly half (48%) have seen or used briquettes, suggesting some market penetration, Adoption potential is high, with 75% willing to adopt if affordable. There's still a training need (78%), indicating that public education will be vital for successful adoption.

Table 7: Adoption Readiness and Awareness Level

Indicator	Azare (%)	Ningi (%)	Toro (%)	Total (%)
Have heard about biomass briquettes	60	72	65	66
Have seen/used briquettes before	45	51	48	48
Willing to adopt if affordable	70	80	76	75
Trust in safety of briquettes	55	60	58	58
Need training before usage	80	75	78	78

Source: Author's Fieldwork, 2024.

4.8 Challenges and Barriers to Biomass Briquette Adoption

Table 8 identifies the primary constraints to adopting biomass briquettes, by percentage of respondents per location, in order to help in designing policy and program interventions to overcome key adoption barriers. Lack of awareness (30.3%) is the most cited barrier, confirming the need for advocacy and sensitization. High initial cost (27.7%) and inconsistent supply (20%) reflect market and production limitations, while Cultural habits still play a role, with 8.3% preferring firewood due to tradition.

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Table 8: Challenges and Barriers to Biomass Briquette Adoption

Challenge	Azare (%)	Ningi (%)	Toro (%)	Total (%)
Lack of awareness	33	28	30	30.3
High initial cost of briquette	25	30	28	27.7
Inconsistent supply chain	18	22	20	20.0
Poor distribution infrastructure	15	14	12	13.6
Cultural preference for firewood	9	6	10	8.3

Source: Author's Fieldwork, 2024.

4.9 Comparative Energy Cost Savings (Briquettes vs Traditional Fuels)

Table 9 offers a cost-benefit analysis of using biomass briquettes compared to other traditional fuels, in order to reinforce the economic and environmental value of briquettes for low-income households, supporting policy recommendations for subsidy or scaling-up production. Biomass briquettes are the cheapest, at ₦7,000 per month on average. They also provide the longest cooking duration per unit (35 hours) and emit the lowest levels of smoke, while firewood and kerosene are more expensive and environmentally damaging, while charcoal falls in between.

Table 9: Comparative Energy Cost Savings (Briquettes vs Traditional Fuels)

Fuel Type	Avg. Monthly Cost (₦)	Cooking Duration per Unit (hrs)	Emission Level
Firewood	₦12,000	30	High
Charcoal	₦10,000	28	Moderate
Kerosene	₦15,000	25	Moderate
Biomass Briquette	₦7,000	35	Low

Source: Author's Fieldwork, 2024.

5.0 Proposed Model for Biomass Briquette Production in Nigeria

This Proposed model as shown in Table 10 and Figure 2 illustrates the Biomass Briquette Value Chain Development (BB-VCD) process in Nigeria, using Bauchi State (Azare, Ningi, and Toro) as case study hubs. This model outlines a systematic, inclusive, and sustainable approach to developing a biomass briquette sector in Nigeria. It bridges urban and rural development**,** clean energy access**,** and climate action**,** aligning with national and global sustainability goals.

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Table 10: BIOMASS BRIQUETTE PRODUCTION

FEEDSTOCK SOURCING
(Agro-residues, community supply)
↓
BRIQUETTE PRODUCTION HUBS
(Azare, Ningi, Toro in Bauchi State)
↓
QUALITY CONTROL & STANDARDIZATION
↓
MARKET DEVELOPMENT & PROMOTION
↓
CAPACITY BUILDING & GOVERNMENT ENGAGEMENT
↓
HOUSEHOLD UTILIZATION & CLIMATE IMPACT
↓
MONITORING, EVALUATION, SCALABILITY

Source: Author's Compilations, 2025.



Figure 2 : Model for Biomass Briquette Value Chain Development (BB-VCD) Nigeria
Source: Author's Compilations, 2025.

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i. **Feedstock Sourcing (Agro-Residues, Community Supply):** This is the first stage where raw materials (e.g., agricultural waste like rice husks, sawdust, groundnut shells, maize stalks) are collected from farms and local communities. It emphasizes local participation and the use of waste-to-resource principles for sustainability.

ii. **Briquette Production Hubs (Azare, Ningi, Toro in Bauchi State):**The collected feedstock is processed in decentralized production hubs located in key areas (Azare, Ningi, and Toro).These serve as innovation and manufacturing centers for converting biomass into briquettes using appropriate technologies.

iii. **Quality Control & Standardization**: At this stage, quality assurance measures are put in place to ensure the briquettes meet energy efficiency, safety, and usability standards**.** It ensures the briquettes can compete with conventional fuels like charcoal or kerosene in the market.

iv. **Market Development & Promotion:** Focuses on creating awareness, market linkage**,** and promoting the economic and environmental benefits of briquette test of households, institutions, and industries. It involves branding**,** pilot demonstrations**,** and distribution networks**.**

v. **Capacity Building & Government Engagement:** This step involves training stakeholders**,** including local entrepreneurs, producers, and community members, on briquette production and business skills. Engaging government agencies and policymakers for support, subsidies, favorable policies, and integration into clean energy programs is also key.

vi. **Household Utilization & Climate Impact:** Households begin to adopt briquettes for cooking and heating. The use of briquettes leads to reduced deforestation**,** lower carbon emissions, and improved indoor air quality**,** contributing to climate change mitigation**.**

vii. **Monitoring, Evaluation, Scalability:** This is the final stage**,** focused on assessing the impact, effectiveness, and challenges of the value chain. It provides insights for replication and scaling the

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model to other regions in Nigeria or across Sub-Saharan Africa.

6.0 Discussion of Findings

Numerous studies have reaffirmed Nigeria's vast and largely untapped biomass energy potential. Jekayinfa et al. (2020) and Akhtar et al. (2024) highlight the abundance of biomass sources agricultural residues, forest waste, and municipal organic waste across the country. These studies establish the foundation for recognizing the potential of biomass as a significant energy resource in Nigeria. Building on this, Kardam et al. (2022) and Okedu et al. (2024) demonstrate how geospatial techniques can identify and map out biomass hotspots specifically within Bauchi State. This methodological contribution is crucial for the strategic siting of biomass conversion facilities, optimizing resource utilization and minimizing transportation costs.

Ibitoye et al. (2023) further provide detailed classifications of biomass sources in Nigeria, emphasizing their morphological and structural diversity, which influence combustion efficiency and energy output. This classification is essential for tailoring briquetting processes to specific biomass feed stocks. Our study builds upon this by providing a detailed quantitative assessment of the specific types and quantities of agricultural residues available in Bauchi State, offering a localized perspective on the national biomass potential. These findings collectively validate the feasibility of deploying localized biomass briquetting initiatives in Bauchi and other parts of Nigeria.

The physical and combustion characteristics of biomass briquettes are greatly influenced by processing parameters such as pressure, binder proportion, retention time, and feedstock composition. Adam et al. (2024) and Ossei-Bremang et al. (2024) demonstrate that increasing compaction pressure and adjusting binder ratios significantly enhances briquette density, durability, and calorific value. This underscores the importance of optimizing the briquetting process to achieve desired fuel properties. Ajimotokan et al. (2019) and Adeleke et al. (2019) report that combining sawdust with charcoal fines or other agro-wastes produces briquettes with superior ignition and combustion qualities, highlighting the potential of blending different biomass materials.

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Furthermore, García et al. (2020) and Sermyagina et al. (2022) indicate that the use of torrefaction and additives improves energy content and reduces moisture sensitivity, addressing challenges related to fuel quality and storage. Our research aligns with these studies by evaluating the combustion properties of briquettes made from a novel combination of agricultural residues prevalent in the region. Nganko et al. (2024) utilize response surface methodology (RSM) to optimize process parameters, providing a valuable methodological framework. Our study adopts and adapts this approach to the specific biomass resources and desired briquette characteristics relevant to Bauchi, aiming to achieve context-specific briquette optimization.

Technological adoption is pivotal for the sustainability of biomass briquetting. Mperejekumana et al. (2024) and Gitau et al. (2019) reveal that cook stove technology, briquette quality, and affordability heavily influence household uptake, especially in rural sub-Saharan Africa. This highlights the crucial role of user-centered design and economic considerations in promoting the adoption of biomass briquettes. Akolgo et al. (2018) demonstrate the dual benefits of improved cook stoves, efficient cooking and biochar production, showcasing the potential for integrated systems.

Similarly, Sharma et al. (2024) and Njenga et al. (2019) advocate for community-based briquetting as a pathway for income generation, gender empowerment, and improved livelihoods, emphasizing the socio-economic benefits of this approach. However, the Punch Newspaper (2024) report and the National Bureau of Statistics (NBS, 2022) data emphasize that Nigeria's clean cooking efforts have been undermined by subsidy removal and poor implementation strategies. This has resulted in persistent energy poverty, particularly in northern states like Bauchi, indicating a disconnect between policy and practice. Our research addresses these challenges by proposing a community-based briquetting model that is specifically tailored to the socio-economic context of Bauchi State, taking into account affordability and accessibility for vulnerable households.

Despite Nigeria's endorsement of renewable energy, as documented in the National

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Renewable Energy Policy (2018) and the National Energy Policy (2022), implementation gaps exist. The Federal Ministry of Environment (2023) has outlined a draft National Clean Cooking Policy, but field reports suggest limited awareness and enforcement, indicating a need for stronger policy implementation. According to Oginni et al. (2019), a lack of political will, financing, and infrastructural support impedes the scaling of renewable energy technologies, including briquetting. This highlights systemic barriers that need to be addressed. ECOWAS (2019) has provided a regional energy protocol that could support biomass standardization and cross-border trade, yet it remains underutilized at the national level.

The IPCC (2021) and IEA (2022) underscore the global urgency for energy transition and highlight biomass as a key renewable pathway, especially for developing economies. Aligning national efforts with international frameworks could provide policy coherence and attract funding. Our work contributes by developing a localized energy planning framework that explicitly integrates biomass briquetting, taking into account the specific policy and institutional context of Bauchi State.

Biomass briquetting offers a win-win for both climate mitigation and forest conservation. Acheampong and Opoku (2023) draw attention to the justice dimensions of energy access, suggesting that biomass solutions can bridge equity gaps if equitably distributed. This emphasizes the importance of ensuring that the benefits of biomass energy are shared by all segments of society. FAO (2022) warns against unsustainable biomass extraction, advocating for circularity and reforestation, highlighting the need for sustainable resource management practices. The work by Prasad and Raturi (2021) and Sharma et al. (2020) suggests that sustainable biomass production, coupled with environmental stewardship, can reduce carbon emissions while improving urban and rural energy access. Meanwhile, Rithuparna et al. (2021) highlight the recycling potential of agro-waste into value-added products, creating a circular economy around biomass energy. Our research reinforces these perspectives by assessing the environmental sustainability of different biomass feed stocks available in the

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region and recommending best practices for sustainable harvesting.

The findings discussed above underscore the significant potential of integrating biomass briquette production into Nigeria's energy planning, particularly for sustainable household utilization and climate resilience in states like Bauchi. The abundance of readily available biomass resources, coupled with advancements in briquetting technology and the potential for community-based models, presents a viable pathway to address energy poverty, reduce reliance on unsustainable fuel sources, and mitigate greenhouse gas emissions. However, realizing this potential requires addressing critical challenges related to policy implementation, financial investment, technological adoption, and ensuring equitable access.

Specifically, our research highlights the need for localized biomass resource management strategies: This includes detailed mapping of biomass availability, sustainable harvesting practices, and efficient supply chain development. Targeted subsidies and awareness campaigns, these are essential to promote the adoption of biomass briquettes, particularly among low-income households, and to educate the public about the benefits of this clean energy source. Quality control standards and certification by establishing and enforcing standards for briquette production will ensure consistent quality, improve consumer confidence, and facilitate market development. These implications provide a foundation for future policy recommendations and interventions aimed at fostering a sustainable and climate-resilient energy future for Nigerian households.

7.0 Conclusion and Recommendation

This study highlights the potential for integrating biomass briquette production into urban energy planning for sustainable household energy utilization and climate resilience in Bauchi State, Nigeria. The findings reveal that biomass feed stocks, such as rice husk, groundnut shells, and sawdust, are abundant and accessible across the region, offering a sustainable alternative to conventional cooking fuels. However, challenges such as lack of infrastructure, low economic feasibility, and limited awareness must be addressed for successful adoption. The

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experimental results demonstrated that biomass briquettes have a higher calorific value, longer combustion time, and lower emissions compared to traditional firewood, confirming their potential in promoting clean energy solutions. Moreover, community acceptance and adoption readiness are moderate, with significant interest in transitioning to briquettes if affordability and accessibility are improved. By implementing these recommendations, Nigeria can effectively integrate biomass briquette production into energy planning, which aligns with Nigeria's climate-resilient urban transition objectives and energy sustainability goals.

1. Establish local production facilities and improve the infrastructure for biomass briquette production to reduce costs and improve accessibility. This can be achieved through pub-lic-private partnerships and government incentives.

2. Increase awareness and knowledge about the benefits of biomass briquettes through community outreach programs and targeted campaigns. This can address the gap in understanding and facilitate wider adoption.

3. Implement subsidies or micro-financing programs to reduce the initial cost of biomass briquettes and production equipment, making it more affordable for households, especial-ly in rural areas.

4. Offer training programs for local communities on the production and proper use of bio-mass briquettes. This will enhance technical expertise and ensure efficient use of re-sources.

5. Advocate for the integration of biomass briquette production into national and state energy policies, ensuring that it is recognized as a key solution in Nigeria's transition to sustainable energy and climate resilience.

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