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Biomass Supply Chain Logistics and Economic Viability for Sustainable Bioenergy Development in Bauchi State, Nigeria

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ABSTRACT
Biomass resources represent an important renewable energy option for enhancing energy security and promoting sustainable rural development in Nigeria; however, inefficient supply chain logistics, inadequate storage infrastructure, and unstable market systems continue to limit their effective utilization. This study assessed the logistics and economic viability of biomass supply chains for sustainable bioenergy development in selected Local Government Areas of Bauchi State, Nigeria, using a mixed-methods research design involving 1,144 biomass stakeholders surveyed through questionnaires, key informant interviews, focus group discussions, and field observations. The results revealed substantial biomass availability of approximately 1,240–1,542 tonnes annually, with sawdust (350–420 tonnes) and rice husks (320–360 tonnes) constituting the dominant feedstocks. Transportation costs varied significantly across locations, ranging from ₦87.57/km in Misau to ₦1,570.53/km in Jama'are, while hidden operational costs ranged between ₦120 and ₦270 per 100 kg bag, reducing overall profitability. Furthermore, biomass trading in Jama'are recorded a 24.84% negative price gap, indicating economic unsustainability, whereas seasonal fluctuations and inadequate storage facilities contributed to supply instability and post-harvest losses. The study concludes that although Bauchi State possesses considerable biomass resources capable of supporting renewable energy development, improving transportation infrastructure, storage facilities, market coordination, and policy support is essential for developing an efficient and economically viable biomass supply chain.

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INTRODUCTION

The global imperative to transition towards sustainable energy sources has intensified in recent decades, driven by concerns over climate change, energy security, and the depletion of fossil fuel reserves (Okoro et al., 2024). In this context, biomass energy has emerged as a promising renewable alternative, offering a pathway to reduce greenhouse gas emissions and foster energy independence. Biomass, defined as organic material derived from plants and animals, harnesses solar energy through photosynthesis, making it a continuously replenishable resource (National Geographic Education, 2026). Its versatility allows for conversion into various forms of energy, including heat, electricity, and biofuels, thereby presenting a multifaceted solution to contemporary energy challenges (U.S. Energy Information Administration, n.d.). Consequently, nations worldwide are increasingly exploring the potential of biomass to diversify their energy portfolios and achieve sustainable development goals.

Nigeria, a country endowed with vast natural resources, faces significant energy deficits, particularly in its rural areas, where access to modern energy services remains limited (Odediran, 2024). The nation's energy sector is predominantly reliant on fossil fuels, a dependency that not only contributes to environmental degradation but also exposes the economy to the volatility of global oil markets (Ogunrewo & Nwulu, 2024). In light of these challenges, biomass energy presents a compelling opportunity for Nigeria to address its energy needs sustainably. Indeed, traditional biomass, primarily in the form of firewood and charcoal, already accounts for a substantial

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portion of Nigeria's energy consumption, contributing up to 74% of the total energy demand (Okoro et al., 2024). This existing reliance underscores the cultural acceptance and inherent potential for modern bioenergy applications, which could significantly improve energy access and reduce the environmental footprint associated with traditional biomass use.

The abundance of biomass resources across Nigeria is a critical factor in its bioenergy potential. The country is rich in various forms of biomass, including agricultural residues, forest residues, municipal solid waste, and animal waste (Jekayinfa et al., 2020). Agricultural residues, in particular, represent a vast and largely untapped resource. Nigeria generates approximately 750 million metric tons of agricultural residues annually, with a significant portion remaining unutilized (Ahmed et al., 2025). These residues, such as cassava peel, maize husk, rice straw, and sorghum bran, can be valorized into valuable bioenergy products, thereby creating a circular economy that minimizes waste and maximizes resource efficiency (Ogunrewo & Nwulu, 2024). The strategic utilization of these resources could not only provide a sustainable energy supply but also generate economic opportunities for rural communities through feedstock cultivation, collection, and processing.

Focusing specifically on Bauchi State, located in the North-Eastern part of Nigeria, the agricultural sector is a cornerstone of the local economy, leading to a substantial generation of lignocellulosic biomass. Research indicates that Bauchi State alone produces over 651,866.8 tons of lignocellulose biomass annually, comprising materials such as sugarcane bagasse, corn stover, groundnut shell, millet residue, sorghum residue, and rice straw (Ibrahim, 2020). This impressive quantity highlights the immense potential for bioenergy development within the state. However, the effective harnessing of these resources is not without its complexities. The transition from raw biomass to usable energy products necessitates a robust and efficient supply chain, encompassing all stages from feedstock sourcing to energy delivery.

Despite the evident potential, the development of a sustainable bioenergy sector in Nigeria, and particularly in Bauchi State, is hampered by significant logistical challenges. The biomass supply chain (BSC) in Nigeria is characterized by inefficiencies stemming from inadequate transportation infrastructure, high transportation costs due to poor road networks, and the low energy density of raw biomass, which makes its transport over long distances economically unviable (Ogunrewo & Nwulu, 2024). Furthermore, the seasonal nature of agricultural production leads to fluctuations in biomass availability, posing challenges for consistent feedstock supply. The lack of appropriate storage infrastructure exacerbates this issue, resulting in substantial post-harvest losses and degradation of biomass quality (Ebisi, 2024). These logistical bottlenecks collectively impede the seamless flow of biomass from farms to processing facilities, thereby undermining the economic viability of bioenergy projects.

Against this backdrop, a discernible research gap exists concerning the integrated analysis of biomass supply chain logistics and economic viability specifically within the context of Bauchi State, Nigeria. While studies have explored biomass resources and bioenergy potential in Nigeria generally, a comprehensive examination that delves into the unique logistical challenges, transportation networks, storage infrastructure, pricing mechanisms, and overall economic feasibility for sustainable bioenergy development in Bauchi State is largely absent. Existing literature often addresses these components in isolation or focuses on other regions, leaving a critical void in understanding the localized dynamics essential for effective policy formulation and investment decisions (Odediran, 2024). Therefore, a focused investigation into these aspects is crucial to unlock the full bioenergy potential of the state and ensure its sustainable development. This study, therefore, aims to examine the logistics, transportation, storage infrastructure, pricing systems, and economic viability of biomass supply chains for sustainable bioenergy development in Bauchi State, Nigeria. By addressing these objectives, this research seeks to provide comprehensive insights that can inform stakeholders, policymakers, and investors, ultimately contributing to the establishment of a robust and sustainable bioenergy sector in Bauchi State, Nigeria.

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LITERATURE REVIEW

The burgeoning interest in bioenergy as a cornerstone of sustainable development has led to extensive research into the intricacies of biomass supply chains (BSCs). Fundamentally, a BSC encompasses the entire journey of biomass, from its initial production and harvesting to its eventual conversion into usable energy forms (Ahmed et al., 2025). This complex network involves a series of interconnected activities, including feedstock collection, preprocessing, storage, transportation, and delivery to biorefineries or energy conversion facilities (Ogunrewo & Nwulu, 2024). The efficiency and sustainability of these chains are paramount, as they directly influence the economic viability and environmental footprint of bioenergy projects. Consequently, a holistic understanding of BSCs necessitates an examination of their various components, the challenges inherent in their operation, and the theoretical frameworks that underpin their optimization.

Biomass Supply Chains

Biomass supply chains are inherently more complex than conventional fossil fuel supply chains due to the diffuse nature of biomass resources, their low energy density, and seasonal availability (Mirkouei et al., 2017). Unlike concentrated fossil fuel deposits, biomass feedstocks are often geographically dispersed, requiring extensive collection and aggregation efforts. This characteristic introduces significant logistical challenges, particularly in regions with underdeveloped infrastructure. Furthermore, the physical and chemical properties of biomass, such as high moisture content and irregular shapes, necessitate preprocessing steps like drying, chipping, or densification (e.g., briquetting) to enhance its energy density and reduce transportation costs (Odediran, 2024). The seasonal variability of agricultural residues, a primary source of biomass in many developing countries, also poses a challenge, demanding effective storage solutions to ensure a continuous supply to conversion facilities (Ahmed et al., 2025).

Research into BSCs often categorizes them into upstream, midstream, and downstream segments. The upstream segment focuses on feedstock production, harvesting, and initial collection. The midstream involves transportation, storage, and preprocessing, while the downstream segment deals with conversion to energy and distribution of bioenergy products (Mirkouei et al., 2017). Each segment presents unique challenges and opportunities for optimization. For instance, in Nigeria, agricultural residues like cassava peel, maize husk, rice straw, and sorghum bran are abundant, yet their collection and aggregation from numerous smallholder farms remain a significant hurdle (Jekayinfa et al., 2020). The development of efficient collection networks and the establishment of aggregation points are crucial for streamlining the upstream segment of the BSC.

Transportation Logistics

Transportation logistics constitute a critical component of the biomass supply chain, often accounting for a substantial portion of the total cost of bioenergy production (Ogunrewo & Nwulu, 2024). The challenge is particularly pronounced in developing countries like Nigeria, where road infrastructure is often poor and transportation networks are inefficient. The low bulk density of raw biomass means that large volumes must be transported, leading to high transportation costs per unit of energy. This economic reality often limits the feasible hauling distance for biomass, thereby restricting the catchment area for biorefineries and potentially leaving vast quantities of biomass resources unutilized (Mirkouei et al., 2017). Consequently, optimizing transportation routes, modes, and vehicle utilization is essential for enhancing the economic viability of bioenergy projects.

Various studies have explored optimization models to address transportation challenges in BSCs. For example, Ogunrewo and Nwulu (2024) utilized Mixed Integer Linear Programming (MILP) and Geographic Information Systems (GIS) to optimize biomass supply chains in Southwest Nigeria, focusing on minimizing transportation costs and maximizing revenue from bioproducts. GIS-based approaches are particularly valuable for identifying optimal locations for collection centers and biorefineries, considering factors such as feedstock availability, road networks, and proximity to markets (Mirkouei et al., 2017). However, these models often need to account for the dynamic nature of biomass supply and

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demand, as well as the inherent uncertainties in fuel prices and road conditions. The development of robust transportation strategies that integrate these complexities is vital for establishing resilient and cost-effective BSCs in regions like Bauchi State.

Storage Infrastructure

Effective storage infrastructure is indispensable for mitigating the challenges posed by the seasonal availability of biomass feedstocks and ensuring a continuous supply to bioenergy conversion facilities. In many agricultural settings, biomass is only available during specific harvesting periods, leading to a surplus immediately after harvest and scarcity during off-seasons. Without adequate storage, this seasonality results in significant post-harvest losses due to spoilage, pest infestation, and degradation, thereby reducing the overall available biomass for energy production (Ebisi, 2024). Furthermore, the lack of proper storage facilities can lead to inefficient resource utilization and increased operational costs for biorefineries that require a steady feedstock supply.

In Nigeria, traditional biomass storage practices often involve open-air piling or rudimentary shelters, which offer minimal protection against environmental elements and biological degradation (Ebisi, 2024). This contributes to the high rates of post-harvest losses observed across the agricultural sector. The development of modern, purpose-built storage facilities, such as covered sheds, silos, or baling and wrapping systems, is crucial for preserving biomass quality and quantity. However, the establishment of such infrastructure requires significant capital investment, which can be a barrier for local communities and small-scale bioenergy producers. Research by Ahmed et al. (2025) highlights that while there has been extensive research on the environmental sustainability of BSCs, the economic aspects of storage infrastructure are often under-represented in existing literature, underscoring a need for more detailed economic analyses of various storage options in the Nigerian context.

Biomass Market Systems

The development of a vibrant and efficient biomass market system is fundamental for fostering sustainable bioenergy development. In many developing economies, including Nigeria, biomass markets are often informal, fragmented, and characterized by a lack of transparent pricing mechanisms (Adeyemi et al., 2012). This informal structure can create uncertainties for both biomass suppliers and off-takers, hindering investment in bioenergy projects. The pricing of biomass feedstocks is influenced by a multitude of factors, including availability, quality, transportation costs, and competing uses (e.g., animal feed, fertilizer). Without a clear and stable pricing system, it becomes challenging to establish long-term supply contracts and ensure the economic viability of bioenergy ventures.

Studies on biomass market systems in Nigeria indicate that the absence of formal market structures and regulatory frameworks contributes to inefficiencies and price volatility. For instance, the pricing of fuelwood, a traditional biomass source, is often determined by local supply and demand dynamics, with significant variations across different regions (Adeyemi et al., 2012). For modern bioenergy applications, a more structured market is required, potentially involving aggregation models, contract farming, and the establishment of biomass exchanges. The integration of biomass briquettes into Nigeria's energy sector, as explored by Odediran (2024), suggests the need for market development strategies that promote the adoption of processed biomass fuels and ensure fair pricing for producers. Furthermore, government policies and incentives play a crucial role in shaping market dynamics and encouraging investment in the bioenergy sector (Okoro et al., 2024).

Economic Viability

The economic viability of bioenergy projects is a critical determinant of their success and sustainability. Investors and policymakers assess viability using various financial metrics, including Net Present Value (NPV), Internal Rate of Return (IRR), and Payback Period (Obileke & Mukumba, 2025). A project is generally considered economically viable if it generates a positive NPV, an IRR that exceeds the cost of capital, and a reasonable payback period. However, bioenergy projects, particularly in developing countries, often face

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significant economic hurdles, including high initial capital costs for conversion technologies, substantial operational expenses related to feedstock procurement and logistics, and uncertainties in market prices for bioenergy products (Ahmed et al., 2025).

Research consistently highlights that transportation and storage costs are major contributors to the overall cost structure of biomass-to-energy pathways, directly impacting economic viability (Mirkouei et al., 2017). Moreover, the scale of operation plays a crucial role, with larger-scale facilities often benefiting from economies of scale, which can reduce per-unit production costs. However, large-scale projects also entail greater investment risks and more complex supply chain management. In the Nigerian context, the economic viability of bioenergy projects is further influenced by factors such as access to finance, government subsidies, and the competitive landscape with conventional fossil fuels (Okoro et al., 2024). Therefore, comprehensive techno-economic assessments that consider all these variables are essential for making informed investment decisions and designing financially sustainable bioenergy initiatives in Bauchi State.

Theoretical Framework

To comprehensively analyze the biomass supply chain logistics and economic viability for sustainable bioenergy development in Bauchi State, this study draws upon several theoretical frameworks. Firstly, the Biomass Value-Web concept, as advanced by Adetoyinbo et al. (2022), offers a robust lens through which to view the interconnectedness and circularity of biomass utilization. Unlike traditional linear value chains, the value-web emphasizes the multiple pathways and interdependencies among various actors and processes involved in transforming biomass into diverse products and services. This framework is particularly relevant for understanding how agricultural residues in Bauchi State can be integrated into a broader bioeconomy, creating synergies and maximizing resource efficiency beyond simple energy conversion.

Secondly, Porter's Diamond Model of National Competitive Advantage provides a framework for assessing the factors that contribute to a region's ability to compete in a particular industry (Porter, 1990). Applied to the bioenergy sector in Bauchi State, this model can help analyze how local factor endowments (e.g., abundant biomass resources, labor), demand conditions (e.g., local energy needs), related and supporting industries (e.g., agricultural machinery, transportation services), and firm strategy, structure, and rivalry influence the development of a competitive bioenergy industry. Furthermore, the role of government policy, as an influencing factor within the diamond, becomes crucial in fostering an enabling environment for bioenergy development.

Finally, Sustainable Supply Chain Management (SSCM) theory offers a guiding principle for integrating environmental and social considerations alongside economic objectives throughout the biomass supply chain (Ahmed et al., 2025). SSCM extends beyond traditional cost and efficiency metrics to include aspects such as environmental impact reduction (e.g., carbon footprint, waste management) and social responsibility (e.g., fair labor practices, community engagement). Given the overarching goal of sustainable bioenergy development, adopting an SSCM perspective ensures that the proposed solutions for logistics, transportation, and storage not only utilisation enhance economic viability but also contribute positively to environmental protection and social welfare in Bauchi State. By combining these frameworks, this research aims to provide a multi-dimensional analysis that captures the complexities of bioenergy development in the region.

METHODOLOGY

This study employed a mixed-methods research design to comprehensively examine biomass resource availability, supply chain dynamics, logistics, and utilization practices across selected Local Government Areas (LGAs) in Bauchi State, Nigeria. The mixed-methods approach was considered appropriate because it enabled the integration of quantitative evidence with qualitative insights, thereby providing a more holistic understanding of the biomass value chain and the socio-economic factors influencing its development. The study adopted a cross-sectional survey design in which data were collected from biomass stakeholders at a single

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point in time to capture prevailing practices, challenges, and opportunities within the sector. Four LGAs Bauchi, Jama'are, Misau, and Tafawa Balewa were purposively selected because of their diverse agricultural activities, abundance of biomass resources, and active participation in biomass generation and utilization. These areas represent different agro-ecological and socio-economic conditions within Bauchi State, making them suitable for comparative analysis and the development of context-specific recommendations for sustainable biomass utilization.

Primary data were collected from 1,144 respondents comprising farmers, agro-processors, market vendors, waste collectors, biomass traders, transporters, community leaders, and relevant government officials involved in biomass production and management. A multi-stage stratified sampling technique was adopted to ensure that the major stakeholder groups within the biomass value chain were adequately represented across the four study areas. Data collection involved the administration of structured questionnaires to obtain quantitative information on biomass types, quantities, seasonal availability, collection practices, transportation logistics, storage conditions, pricing structures, utilization patterns, and stakeholder characteristics. To enrich and validate the survey findings, qualitative data were obtained through key informant interviews, focus group discussions, and field observations involving experienced practitioners and local stakeholders with extensive knowledge of biomass production and utilization systems. This triangulation of data sources enhanced the credibility and reliability of the findings while providing deeper contextual understanding of operational constraints and emerging opportunities within the biomass sector.

The collected data were analyzed using descriptive statistical techniques, including frequencies, percentages, means, and comparative analyses to examine variations among the four LGAs. Biomass feedstocks were assessed with respect to their spatial distribution, seasonal availability, supply chain characteristics, market dynamics, and utilization practices, while qualitative responses were analyzed thematically to identify recurring patterns relating to logistics challenges, infrastructure deficiencies, economic viability, and stakeholder participation. The integration of quantitative and qualitative evidence facilitated a comprehensive interpretation of the biomass value chain and supported the development of practical recommendations for improving biomass resource management and sustainable bioenergy development. The methodological approach adopted in this study provides a robust empirical basis for evaluating biomass systems and offers a replicable framework for similar studies in other agrarian regions seeking to harness biomass resources for renewable energy generation and sustainable economic development.

RESULTS AND DISCUSSION

Biomass Feedstock Availability Results

The findings indicate the presence of substantial biomass resources across the four study LGAs, demonstrating significant potential for biomass-based energy development. Agricultural residues, particularly rice husks, sorghum stalks, millet husks, maize stalks, and corn cobs, constituted the major feedstocks available within the study area. In addition, sawdust generated from timber processing activities and organic market waste provided important supplementary biomass resources. Estimated annual biomass generation ranged between 215 and 442 tonnes across the LGAs, with total biomass availability exceeding 1,200 tonnes annually. Sawdust and rice husks emerged as the most abundant and consistently available feedstocks, while crop residues such as sorghum stalks and millet husks exhibited greater seasonal variability. These findings suggest that Bauchi State possesses a diverse biomass resource base capable of supporting decentralized bioenergy initiatives if supported by efficient collection and utilization systems. The observed variation among LGAs further indicates the need for location-specific biomass management strategies that reflect local production patterns and resource availability.

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Table 1: Estimated Annual Biomass Generation by LGA (tonnes)

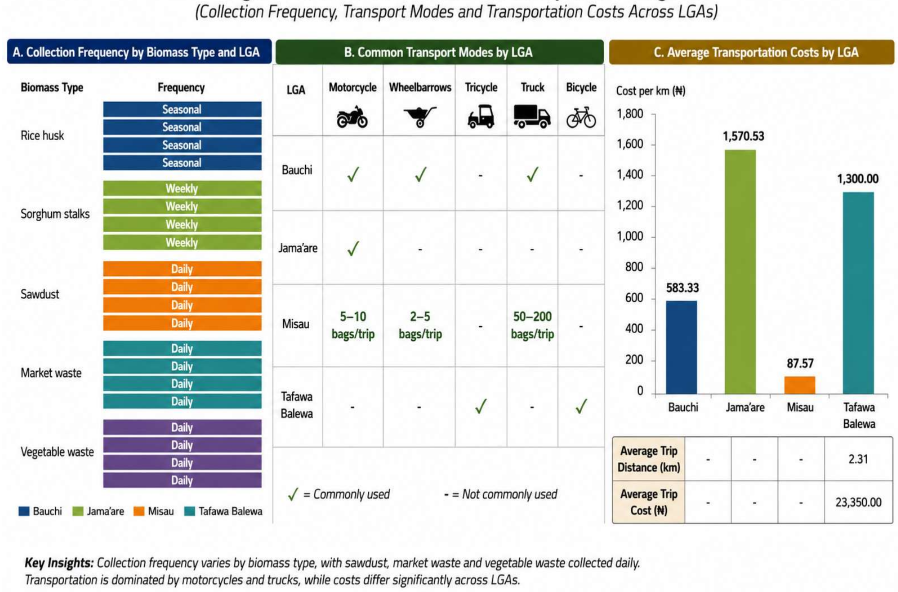
Biomass Type	Bauchi	Jama'are	Misau	Tafawa Balewa	Total
Rice Husk	90-100	90-100	50-60	90-100	320-360
Sorghum stalks	60-80	60-80	60-80	5-7	185-247
Millet husks	40-60	40-60	40-60	5-7	125-187
Maize stalks	10-15	10-15	10-15	10-15	40-60
Corn cobs	5-7	5-7	5-7	5-7	20-28
Sawdust	100-120	100-120	100-120	50-60	350-420
Market waste	50-60	50-60	50-60	50-60	200-240
Total	**355-442**	**355-442**	**315-402**	**215-256**	**1,240-1,542**

Source: Compiled from survey data and Sani Ali (2025a, 2025b, 2025c, 2025d)

Collection Practices and Transportation Logistics

Biomass collection practices varied according to feedstock type and perishability. Agricultural residues such as rice husks were generally collected seasonally following harvest periods, whereas sawdust, market waste, and vegetable waste required daily collection due to their continuous generation and susceptibility to deterioration. The transportation system was dominated by small-scale transport modes including motorcycles, wheelbarrows, bicycles, and tricycles, while trucks were primarily used for long-distance bulk transportation. This pattern reflects the fragmented and informal nature of the biomass supply chain. Transportation costs varied considerably across the study area, ranging from ₦87.57 per kilometre in Misau to ₦1,570.53 per kilometre in Jama'are. Such disparities suggest substantial differences in road quality, accessibility, vehicle availability, and market connectivity. High transportation costs represent one of the most critical constraints affecting biomass commercialization because they increase the delivered cost of biomass and reduce profit margins for suppliers and traders. The findings underscore the importance of improving rural road infrastructure and establishing strategically located aggregation centres to reduce transportation distances and logistics expenses.

Figure 1: Collection Practices and Transportation Logistics
(Collection Frequency, Transport Modes and Transportation Costs Across LGAs)



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Storage Infrastructure and Biomass Handling Findings

The assessment of storage infrastructure revealed significant deficiencies across the biomass value chain. Approximately half of the biomass resources in the surveyed LGAs were stored under uncovered conditions, exposing feedstocks to rainfall, excessive sunlight, pest infestation, and moisture absorption. Such conditions contribute to biomass deterioration, lower calorific value, and increased post-harvest losses. Storage limitations were consistently identified as one of the major operational challenges facing stakeholders. Similarly, biomass handling activities were largely manual in Bauchi, Jama'are, and Misau, where more than 80% of respondents relied on manual labour for loading, unloading, and processing activities. The dependence on manual handling reduces operational efficiency, increases labour requirements, and limits the scale of biomass operations. Only Tafawa Balewa demonstrated a relatively high level of mechanization, suggesting that investment in handling equipment can significantly improve biomass management efficiency. These findings indicate that upgrading storage and handling infrastructure is essential for improving feedstock quality, minimizing losses, and enhancing overall supply chain performance.

Table 2: Biomass Handling Methods by LGA

LGA	Manual Handling	Mechanized Handling	Mixed Method
Bauchi	88.9%	4.8%	-
Jama'are	>50%	-	-
Misau	89.2%	4.8	-
Tafawa Balewa	15.7%	72.7%	11.6%

Pricing Structures, Hidden Costs, and Economic Viability Findings

Biomass pricing varied considerably across feedstock types, seasons, and locations. Rice husks, sorghum stalks, and corn cobs experienced notable seasonal price fluctuations, with prices increasing significantly during the dry season due to reduced availability and increased demand. Seasonal price increases of between 20% and 50% were observed for major feedstocks, creating uncertainty for both suppliers and end-users. Beyond direct transaction prices, stakeholders incurred substantial hidden costs associated with loading, storage, spoilage, and handling. These hidden costs ranged from approximately ₦120 to ₦270 per 100 kg bag and significantly affected actual profitability. Price gap analysis further revealed important variations in economic viability across LGAs. While Bauchi and Tafawa Balewa recorded positive margins between current selling prices and minimum viable prices, Jama'are exhibited a substantial negative gap of approximately 24.84%, indicating that prevailing market prices were insufficient to fully cover operational costs. Misau also recorded a slight negative margin. These findings suggest that many biomass suppliers operate under economically challenging conditions, which may discourage long-term participation in the sector. Consequently, interventions aimed at reducing logistics costs, improving storage facilities, promoting mechanization, and strengthening market coordination are necessary to enhance the financial sustainability of biomass value chains.

Table 3: Biomass Pricing by Type and LGA (₦ per 100kg bag)

Biomass Type	Bauchi	Jama'are	Misau	TBalewa
Rice Husk (harvest)	1,000 – 1,500	300-500	300-500	300-500
Rice husk (dry season)	2,500-4,500	800-1,500	800-1,500	800-1,500
Sorghum stalks (harvest)	1,000-1,500	300-500	300-500	300-500
Sorghum stalks (dry season)	2,500-4,500	850-1,500	850-1,500	-
Sawdust	1,000-1,500	300-400	300-400	300-400
Market waste	-	200-300	200-300	200-300
Corn cob	1,000-1,500	300-500	300-500	300-500

Source: Sani Ali (2025a, 2025b, 2025c, 2025d)

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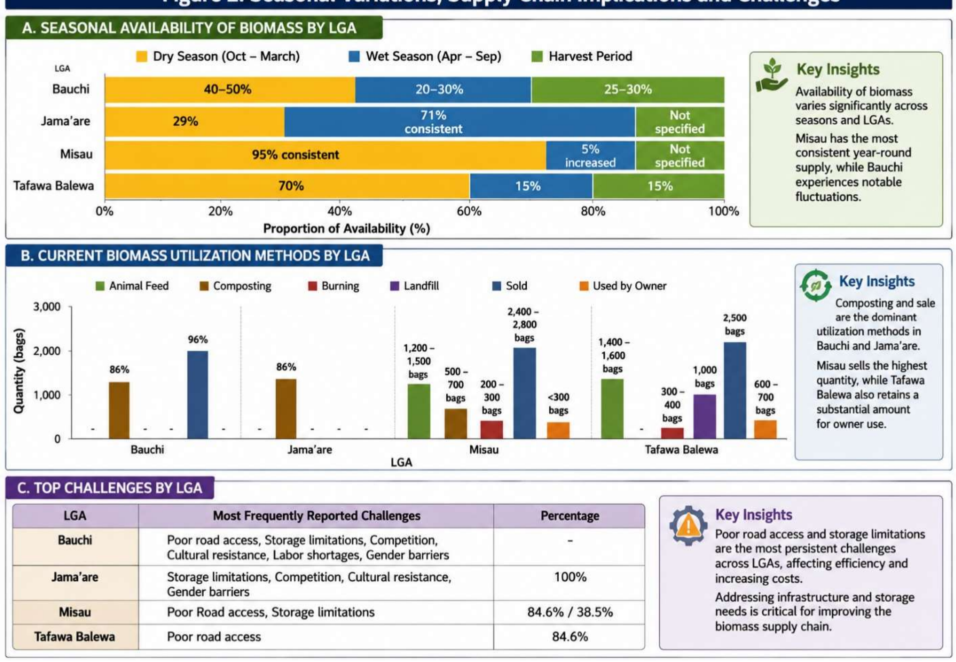
Table 4: Hidden Costs by LGA (₦ per 100kg bag)

Cost Type	Bauchi	Jama'are	Misau	T\Balewa
Loading fee	100-150	50-100	50-100	50-100
Storage cost	50-70	50-100	50-70	varies
Spoilage/losses	20-50	20-30	20-30	varies
Total Hidden Costs	**170-270**	**120-230**	**120-200**	**Variable**

Seasonal Variations, Supply Chain Implications and Challenges

The findings reveal that biomass availability and utilization patterns vary considerably across the four study LGAs, reflecting differences in agricultural production systems and local supply chain dynamics. While Misau demonstrates the most stable year-round biomass supply, Bauchi and Tafawa Balewa experience greater seasonal fluctuations that influence feedstock accessibility and market prices. Biomass utilization remains dominated by composting, animal feed, and direct sales, although substantial quantities continue to be underutilized or disposed of through burning and landfill practices, representing both economic losses and environmental concerns. Across the study area, poor road infrastructure and inadequate storage facilities emerged as the most persistent constraints affecting efficient biomass collection, transportation, and commercialization. Additional challenges, including competition for biomass resources, labour shortages, cultural barriers, and gender-related limitations, further reduce supply chain efficiency. Overall, the results highlight the need for improved storage infrastructure, better transportation networks, and integrated biomass management strategies to ensure a reliable, sustainable, and economically viable biomass supply chain capable of supporting renewable energy development in Bauchi State

Figure 2: Seasonal Variations, Supply Chain Implications and Challenges



CONCLUSION

The study examined biomass feedstock availability, collection practices, transportation logistics, storage infrastructure, pricing structures, and economic viability across selected Local Government Areas in Bauchi State, Nigeria. The findings demonstrate that the study area possesses substantial biomass

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resources capable of supporting sustainable bioenergy development and contributing to rural economic growth. Despite the abundance of agricultural residues, sawdust, and market waste, the biomass supply chain remains constrained by inefficient collection systems, high transportation costs, inadequate storage facilities, limited access to drying infrastructure, and heavy reliance on manual handling methods. Significant seasonal fluctuations in biomass availability further exacerbate supply instability and market inefficiencies, while hidden operational costs reduce profitability and threaten the long-term viability of biomass enterprises in some locations. The study therefore concludes that the sustainability and competitiveness of biomass value chains in Bauchi State depend largely on improving logistics efficiency, strengthening infrastructure, reducing transaction costs, and enhancing market coordination. Addressing these challenges will not only improve biomass utilization but also support renewable energy development, environmental sustainability, and livelihood enhancement within the study area.

RECOMMENDATIONS

1. The Bauchi State Government should improve rural road infrastructure and establish biomass aggregation centres to enhance supply chain efficiency and reduce transportation costs.
2. Relevant government agencies and development partners should invest in modern storage, drying, and biomass handling facilities to reduce post-harvest losses and ensure year-round biomass availability.
3. Financial institutions and policymakers should promote formal biomass markets, cooperative systems, and accessible financing to improve the profitability of biomass enterprises.
4. Government and private sector stakeholders should strengthen investment and policy support for biomass-to-energy technologies to accelerate sustainable renewable energy development in Bauchi State.

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