Innovations in Biomass and Bioenergy: Addressing Energy Poverty in Rural Africa

Akinbobola, Sunday Oluwagbemileke
Department of Chemical Engineering, University of Ilorin, Nigeria.
Email: lekeakinbobola@gmail.com

Anyanwu, Leycot
Department of Communications,
The Hague University of Applied Sciences, Netherlands.
ORCID: 0009-0004-3914-0454
Email: leycots@gmail.com

Galadima, Zubairu Khalifa
Agribusiness Innovation, Africa Business School,
Mohammed VI Polytechnic University, Morocco.
Email: Zubairu.GALADIMA@um6p.ma

Raymond Edward Ereh
Mechanical Engineer and Nuclear Specialist.
Email: raymondereh@rocketmail.com
DOI: 10.56201/ijccp.vol.11.no2.2025.pg61.77

Abstract
This study critically examines the role of biomass and bioenergy innovations in mitigating rural energy poverty in sub-Saharan Africa, with a focused comparative analysis of Nigeria and Uganda. Utilizing a qualitative secondary research approach, the study synthesizes policy reviews, technological advancements, and case study analyses to evaluate the technical feasibility, socio-economic impacts, and implementation challenges of biomass energy solutions. Key innovations□including gasification, pyrolysis, biogas digesters, and cellulosic bioethanol production□demonstrate significant potential for providing decentralized, renewable energy while enhancing agricultural productivity and environmental sustainability. Despite progressive policy frameworks such as Nigeria□s National Renewable Energy and Energy Efficiency Policy (NREEEP, 2015) and Uganda□s Renewable Energy Policy (2007), widespread adoption remains constrained by infrastructural inadequacies, financial barriers, institutional fragmentation, and socio-cultural resistance. Successful localized initiatives, such as Nigeria□s Ibadan biogas-to-electricity project and Uganda□s □Green Heat□ briquette program, highlight pathways for scalable and inclusive bioenergy deployment. The study advocates for integrated policy coordination, increased investment through public-private partnerships, community-based financing mechanisms, and targeted subsidies to unlock the sector□s full potential. Recommendations for future research include exploring cross-border biomass trade, conducting comprehensive life-cycle emission analyses, and leveraging digital technologies for optimizing bioenergy systems, thereby advancing sustainable and equitable rural energy transitions in Africa.

***Keywords**: Biomass energy, rural electrification, bioenergy innovations, Nigeria, Uganda, renewable energy policy, sustainable development, circular economy, energy access.*

1. Introduction

Access to energy is a fundamental driver of economic development, social inclusion, and environmental sustainability. Yet, over 600 million Africans live without electricity, most of them in rural areas (IEA, 2021). This energy poverty impedes education, healthcare delivery, agricultural productivity, and income generation. In Sub-Saharan Africa, biomass remains the primary energy source for rural households, often in the form of firewood or charcoal, which contributes to deforestation, indoor air pollution, and negative health outcomes (Giwa et al., 2017; Dahunsi et al., 2020). With the growing global emphasis on renewable energy and sustainable development, biomass and bioenergy technologies have gained considerable attention as promising alternatives to fossil-based and centralized grid-dependent systems. Unlike conventional energy systems, which often fail to reach dispersed rural populations, bioenergy technologies can be deployed at various scales□from small household biogas units to community-level bio-power plants□making them particularly suitable for off-grid and rural electrification efforts in Sub-Saharan Africa (Ben-Iwo et al., 2016; Chukwuma et al., 2021a). Bioenergy offers a decentralized and context-specific energy solution that leverages the abundant and underutilized local biomass resources in African countries□such as agricultural residues (e.g., cassava peels, rice husks), municipal solid waste, livestock manure, and other forms of organic waste□for electricity generation, cooking, heating, and even transportation fuels (Ayodele et al., 2017; Elum et al., 2017). These feedstocks are not only renewable and widely available, but also offer the added benefit of addressing waste management challenges in rural and peri-urban settings.

Importantly, bioenergy systems contribute to the reduction of greenhouse gas emissions by displacing the use of kerosene, diesel, and unsustainably harvested firewood, which are prevalent in rural areas. Studies have shown that shifting to clean biomass technologies can significantly reduce indoor air pollution, a major cause of respiratory illness, especially among women and children (Dahunsi et al., 2020; Giwa et al., 2017). Furthermore, the establishment of biomass energy systems promotes rural job creation, entrepreneurship, and income diversification across various stages of the bioenergy value chain□including feedstock collection, processing, equipment maintenance, and energy distribution (Awoyale & Lokhat, 2019; Mohammed et al., 2014). In addition to these socioeconomic benefits, the integration of bioenergy into national energy portfolios supports the achievement of multiple Sustainable Development Goals (SDGs), particularly SDG 7 (affordable and clean energy), SDG 13 (climate action), and SDG 8 (decent work and economic growth). However, realizing the full potential of bioenergy in rural Africa requires coordinated policies, capacity-building initiatives, financial incentives, and investment in localized technological innovation (Chukwuma et al., 2021b; Dunmade et al., 2020).

In Nigeria, biomass constitutes approximately 80% of total energy consumption in rural areas, primarily in the form of firewood and agricultural residues (Mohammed et al., 2014). This heavy reliance on traditional biomass is not only inefficient but also poses significant health and environmental risks, including deforestation, indoor air pollution, and soil degradation. The continued use of rudimentary cooking methods, such as open fires and three-stone stoves, has led to high levels of respiratory illnesses and increased labor burdens, particularly for women and children tasked with fuel collection (Elum et al., 2017). Uganda faces comparable challenges, with more than 90% of its rural population dependent on wood fuel for cooking and heating (Dunmade et al., 2020). Access to modern energy services remains low, limiting opportunities for education, healthcare, and economic productivity in remote communities. Moreover, the overexploitation of forest resources for biomass contributes to land degradation and carbon emissions, undermining the country□s environmental sustainability goals (Chukwuma et al., 2021a). Despite these challenges, both Nigeria and Uganda are making strides toward modernizing their biomass sectors through innovative technologies and decentralized energy solutions. Waste-to-energy systems that convert municipal solid waste and agro-industrial byproducts into electricity are gaining traction, particularly in peri-urban zones where waste accumulation is a pressing concern (Chukwuma et al., 2021b). Similarly, biogas digesters, which use livestock manure and organic waste to produce methane for cooking and lighting, have been piloted with success in farming communities, offering a clean and renewable energy alternative while reducing reliance on forest-based fuels (Ayodele et al., 2017).

In addition, bioethanol production from cassava, maize, and sugarcane has shown promise in both countries as a clean cooking fuel and potential transport fuel. These technologies not only enhance energy access but also contribute to rural employment, agricultural value addition, and improved public health outcomes (Ben-Iwo et al., 2016; Awoyale & Lokhat, 2019). However, scaling these innovations requires supportive policies, financial investments, and robust stakeholder collaboration to ensure sustainability, affordability, and local capacity building (Dunmade et al., 2020; Elum et al., 2017). This paper explores how innovations in biomass conversion and bioenergy utilization can reduce energy poverty in rural Africa, focusing on Nigeria and Uganda as illustrative case studies. It critically examines recent technological developments, assesses biomass resource availability, and evaluates the socio-economic and environmental implications of bioenergy deployment in off-grid communities.

2. Theoretical Framework

This study is anchored in the energy justice framework, which emphasizes fairness in the distribution of energy services (distributional justice), inclusive participation in energy decision-making (procedural justice), and the recognition of the specific needs and vulnerabilities of marginalized populations (recognition justice) (Sovacool et al., 2017). In the context of rural Africa, where systemic inequalities persist in energy provisioning, this framework provides a critical lens for evaluating how biomass and bioenergy technologies can be deployed equitably. It challenges technocentric approaches by highlighting the social, economic, and cultural dimensions of energy access. For instance, energy justice calls attention to the burdens rural women bear in collecting firewood and the health risks they face from indoor air pollution□issues that are often overlooked in mainstream energy planning (Heffron & McCauley, 2017).

In tandem, this study draws on the energy ladder model to analyze household energy transition dynamics. The model posits a linear progression in household fuel use from traditional biomass sources (e.g., firewood, dung) to transitional fuels (e.g., charcoal, kerosene), and ultimately to modern energy carriers such as electricity, LPG, biogas, or ethanol (Heltberg, 2004). However, recent scholarship has critiqued the linearity of this model, suggesting that households often "stack" multiple fuels rather than entirely abandoning traditional sources a practice known as fuel stacking (Masera et al., 2000). This phenomenon is particularly prevalent in rural Africa due to economic constraints, fuel availability, and cultural preferences. Therefore, while the energy ladder model provides a useful starting point for understanding energy transitions, this study integrates more nuanced interpretations that consider the socio-economic and institutional barriers to full adoption of modern bioenergy technologies (van der Kroon et al., 2013). Together, the energy justice framework and the energy ladder model offer a comprehensive theoretical basis for analyzing the deployment of biomass and bioenergy solutions in Nigeria and Uganda. They enable a multi-dimensional assessment that goes beyond technological feasibility to include questions of equity, inclusiveness, and long-term sustainability.

3. Literature Review

Sub-Saharan Africa possesses vast biomass resources that remain largely untapped despite their potential to address persistent energy poverty, especially in rural areas. Biomass comprises organic materials derived from plants and animals, including agricultural residues, forestry by-products, animal waste, and municipal solid waste. Studies emphasize the continent s significant biomass endowment, pointing to its suitability for conversion into clean and renewable forms of energy (Ben-Iwo et al., 2016; Awoyale & Lokhat, 2019). In Nigeria, biomass is the most widely used energy source in rural communities, accounting for an estimated 80% of household energy consumption (Mohammed et al., 2014). The country produces more than 144 million tonnes of biomass annually from agricultural waste, including cassava peels, rice husks, sugarcane bagasse, maize stalks, and groundnut shells (Ben-Iwo et al., 2016). Despite this vast resource potential, its utilization remains inefficient and largely traditional, relying on open fires and rudimentary stoves that result in significant energy loss and adverse health outcomes. Uganda presents a similar pattern, with over 90% of its rural population depending on firewood and charcoal for cooking (Chukwuma et al., 2021b). This heavy dependence on traditional biomass leads to several negative environmental and social consequences, including deforestation, loss of biodiversity, and greenhouse gas emissions (Awoyale & Lokhat, 2019).

Moreover, traditional biomass use has been strongly linked to indoor air pollution, which contributes to respiratory infections, particularly among women and children who are more frequently exposed due to their roles in cooking and household chores. According to Elum et al. (2017), exposure to smoke from firewood and charcoal stoves is one of the leading causes of chronic respiratory illnesses and premature deaths in low-income rural households. Additionally, the labor-intensive process of gathering fuelwood often undertaken by women and girls limits their time for education and income-generating activities, thereby reinforcing cycles of poverty and gender inequality (Dahunsi et al., 2020). The inefficient nature of traditional biomass use also exacerbates energy insecurity. With forests depleting rapidly, rural households must travel longer distances to collect firewood, increasing physical burden and vulnerability. Chukwuma et al. (2021a) highlight that in both Nigeria and Uganda, the overharvesting of biomass resources without adequate reforestation or sustainable harvesting practices is unsustainable and poses long-term risks to ecological stability. These challenges underscore the urgent need for transitioning to modern bioenergy solutions such as improved cookstoves, biogas systems, and biomass gasifiers, which offer cleaner, more efficient, and environmentally sustainable alternatives.

Emerging technologiessuch as biogas digesters, bioethanol production systems, and pyrolysis unitsare increasingly being deployed across various contexts in Sub-Saharan Africa to modernize biomass utilization and address rural energy deficits. These innovations are particularly relevant in countries like Nigeria and Uganda, where biomass is abundant but traditionally underutilized in its raw form. Awoyale and Lokhat (2019) explored the viability of small-scale pyrolysis units in rural Nigeria, noting their capacity to convert agricultural waste into bio-oil and biochar. Bio-oil serves as a potential substitute for kerosene in lighting and cooking, while biochar enhances soil fertility and can reduce the need for synthetic fertilizers, contributing to both energy and agricultural sustainability. Similarly, Ezealigo et al. (2021) investigated the production of bioethanol from cassava wastea readily available feedstock in Nigeriaand demonstrated its potential to serve as a clean-burning fuel for cooking and transportation. The study emphasized that cassava peels, when subjected to fermentation and distillation processes, yield high-grade ethanol with significant calorific value. Such bioethanol initiatives are particularly promising because they reduce dependency on imported petroleum products while fostering rural economic development through job creation and local value chain integration.

Biogas technology is also gaining momentum, particularly in Uganda, where dung and organic waste are being harnessed in household-scale digesters to produce methane gas for cooking and lighting (Chukwuma et al., 2021b). These systems not only reduce indoor air pollution but also produce slurry that can be used as organic fertilizer, further contributing to environmental sustainability. According to Dahunsi et al. (2020), the scalability of biogas systems is feasible in East and West Africa, especially when supported by appropriate financing mechanisms and technical training. These decentralized bioenergy technologies offer renewable, affordable, and context-specific solutions that align with the United Nations Sustainable Development Goals (SDGs), particularly SDG 7 on affordable and clean energy, SDG 13 on climate action, and SDG 1 on poverty alleviation. Furthermore, by utilizing locally available feedstocks such as cassava peels, maize cobs, animal waste, and rice husks, these systems reinforce energy sovereignty and reduce vulnerability to global energy market fluctuations (Ben-Iwo et al., 2016). Despite these advantages, challenges remain. Many rural communities lack access to technical knowledge, startup capital, and institutional support to adopt and maintain such systems effectively. This underlines the need for targeted policy interventions, public-private partnerships, and sustained investment in research and capacity building to unlock the full potential of modern biomass technologies in Africa.

Despite their proven technical feasibility and environmental benefits, bioenergy technologies face numerous systemic and structural barriers that continue to hinder their large-scale adoption and integration into national energy strategies. Dahunsi et al. (2020) highlight that institutional fragmentation, unclear regulatory frameworks, and weak enforcement mechanisms have stifled the growth of biomass-based energy systems in countries like Nigeria and Uganda. Often, responsibilities for energy planning and bioenergy development are dispersed among various ministries and agencies, leading to duplication of efforts and policy inconsistencies. Furthermore, a critical obstacle remains the chronic underfunding of bioenergy projects. The sector suffers from limited access to finance, particularly for small and medium-sized enterprises (SMEs) and rural cooperatives that form the backbone of community-level energy initiatives. Without structured financial instrumentssuch as subsidies, grants, and low-interest loansentrepreneurs and local stakeholders find it difficult to scale up bioenergy technologies. Elum et al. (2017) underscore that the lack of public-private partnerships has curtailed innovation and discouraged foreign and domestic investment in the sector. In addition to financial and institutional constraints, the bioenergy landscape is hampered by insufficient investment in research, development, and capacity building. According to Ben-Iwo et al. (2016), the absence of localized data on biomass feedstock availability, conversion efficiency, and socio-economic impacts limits effective planning and policy formulation. This gap is further exacerbated by a lack of technical training programs and skilled labor, which are crucial for the operation, maintenance, and scaling of advanced bioenergy systems such as pyrolysis units and anaerobic digesters.

Socio-cultural factors also pose significant barriers. Traditional beliefs, lack of awareness, and resistance to unfamiliar technologies often impede community uptake. In many rural areas, households continue to rely on firewood and charcoal due to entrenched habits and perceived reliability, despite the known health and environmental risks. Elum et al. (2017) stress the importance of inclusive sensitization campaigns that not only educate rural populations about the benefits of modern bioenergy but also involve them in decision-making processes to ensure local ownership and sustainability. These complex challenges demand a multidimensional response. Strengthening institutional frameworks, fostering cross-sectoral coordination, improving access to finance, and prioritizing community engagement are critical steps toward mainstreaming bioenergy in Sub-Saharan Africa. Without these measures, even the most promising bioenergy technologies may remain underutilized, leaving rural populations locked in cycles of energy poverty and environmental degradation.

Spatial planning and infrastructure optimization remain central challenges in the deployment and scaling of bioenergy technologies across Sub-Saharan Africa. The complexity of collecting, transporting, and processing biomass feedstock often dispersed across vast and inaccessible rural areas necessitates precise, data-driven planning to ensure efficiency and sustainability. In this context, Chukwuma et al. (2021a) emphasize the transformative role of Geographical Information Systems (GIS) in enabling strategic biomass resource mapping and infrastructure planning. Their study illustrates how GIS applications can identify biomass-rich zones, estimate feedstock availability, and determine optimal sites for biogas and bioethanol production facilities based on proximity to raw materials, road access, and population centers. By integrating spatial analysis into energy planning, GIS tools not only enhance the accuracy of decision-making but also minimize environmental degradation and reduce logistical costs, thereby improving the economic viability of bioenergy investments. Moreover, GIS mapping has been used to support waste-to-energy projects by identifying hotspots of municipal solid waste generation and linking them to potential energy demand centers. This spatial integration can inform decentralized energy systems that are more resilient and responsive to local needs (Chukwuma et al., 2021b). Such approaches are particularly relevant in countries like Nigeria and Uganda, where centralized electricity grids are unreliable or nonexistent in many rural communities.

Beyond technical planning, the integration of bioenergy into broader agricultural value chains offers multifaceted development benefits. Awoyale and Lokhat (2019) argue that coupling energy production with agricultural processes such as utilizing cassava peels or maize stalks for biogas or pyrolysis can generate additional revenue streams for farmers and agro-processors. The co-products of bioenergy systems, such as biochar, can be returned to the soil to enhance fertility, water retention, and crop yields, promoting circular economy practices. These innovations not only improve rural livelihoods and food security but also reduce dependence on imported fossil fuels, thus contributing to national energy security and climate goals.bDespite these promising synergies, realizing the full potential of bioenergy integration requires robust institutional and policy frameworks. As Dahunsi et al. (2020) note, the absence of coordinated governance structures, clear land-use policies, and long-term investment incentives has limited the effective implementation of spatially optimized bioenergy systems. Furthermore, without reliable data, inter-ministerial collaboration, and sustained capacity-building efforts, GIS and other planning tools may remain underutilized. To overcome these constraints, governments must prioritize the development of bioenergy master plans that incorporate spatial analytics, align with rural development strategies, and actively engage local stakeholders. Ultimately, the convergence of spatial technologies, agricultural integration, and strong policy support presents a viable pathway for addressing energy poverty, stimulating rural economies, and advancing sustainable development in Sub-Saharan Africa.

4. Methodology

This study employs a qualitative research design, relying primarily on secondary data sources. A systematic content analysis was conducted on peer-reviewed journal articles, policy documents, and technical reports published between 2012 and 2024. These materials were selected based on their relevance to biomass energy technologies, rural energy access, and sustainable development in Sub-Saharan Africa. The countries of Nigeria and Uganda were chosen as case studies due to their contrasting socio-economic contexts, availability of biomass resources, and varying approaches to bioenergy deployment. This comparative framework enables a deeper understanding of both the opportunities and challenges associated with bioenergy adoption in rural African settings.

5. Case Study Analysis

5.1 Nigeria

Nigeria holds one of the highest potentials for biomass energy in Sub-Saharan Africa, with over 144 million tonnes of biomass waste generated annually from agricultural residues such as cassava peels, rice husks, maize stalks, groundnut shells, and sugarcane bagasse (Ben-Iwo et al., 2016). These vast resources, if effectively harnessed, could significantly contribute to energy access, particularly in rural and peri-urban communities where over 80% of households rely on traditional biomass for cooking and heating (Mohammed et al., 2014). In recognition of this potential, the National Renewable Energy and Energy Efficiency Policy (NREEEP, 2015) was introduced as part of Nigeria□s broader efforts to diversify its energy mix and improve energy access. The policy identifies biomass as a key pillar for achieving energy sustainability, reducing greenhouse gas emissions, and promoting rural electrification. It encourages the development of technologies such as biogas digesters, bioethanol plants, and biomass gasifiers. However, the translation of this policy into large-scale implementation has been slow and fragmented.
According to Dahunsi et al. (2020), the major barriers to bioenergy expansion in Nigeria include institutional fragmentation, lack of regulatory clarity, and inconsistent policy support. Multiple agencies often have overlapping mandates, which creates inefficiencies and confusion among

investors and developers. In addition, there is limited financing support and an absence of incentives for private-sector participation, which hampers the scale-up of projects. A prominent example that showcases the promise of bioenergy technology in Nigeria is the Ibadan biogas-to-electricity initiative, where municipal solid waste is converted into biogas to generate approximately 1.2 megawatts (MW) of electricity for local use (Ayodele et al., 2018). This project illustrates the feasibility of waste-to-energy systems in Nigeria's urban centers, especially given the volume of organic waste generated in cities. The co-benefits of such systems include waste management, energy generation, and employment creation. Nonetheless, Ayodele et al. also note that these projects remain isolated and donor-driven, lacking the necessary support from national energy planning frameworks.

Moreover, Elum et al. (2017) argue that many bioenergy initiatives in Nigeria do not prioritize community engagement and often overlook the socio-cultural dimensions of energy use. As a result, rural populations—especially women, who are the primary users of household energy—are frequently excluded from the planning and implementation of new technologies. This leads to resistance or misuse of provided equipment. Public awareness about modern biomass technologies also remains low. The continued dominance of firewood and charcoal use reflects both limited energy literacy and the unaffordability of alternative energy solutions. In many communities, traditional cooking methods are deeply entrenched, and without sustained sensitization campaigns, behavior change is unlikely.

5.2 Uganda

Uganda presents a compelling case of how biomass can be effectively integrated into national and local energy strategies to combat rural energy poverty. With over 90% of the population—particularly in rural areas—depending on biomass, such as firewood and charcoal, for cooking, the country has long recognized the need to modernize its biomass energy systems (Chukwuma et al., 2021b). The Renewable Energy Policy (2007) was a key turning point, as it formally acknowledged biomass as the dominant energy source in Uganda and emphasized the need for cleaner, more efficient technologies. The policy promotes the deployment of improved cookstoves and biogas digesters, especially in off-grid and low-income communities. These technologies aim to mitigate environmental degradation and improve public health, given the significant impact of indoor air pollution from traditional cooking practices (Elum et al., 2017).

One of the most impactful innovations is the Green Heat Uganda initiative, which manufactures bio-briquettes from agricultural waste, including maize cobs, banana peels, coffee husks, and sawdust. These briquettes are used as cleaner alternatives to charcoal, contributing to reduced deforestation and lower greenhouse gas emissions. This initiative exemplifies a circular economy model, turning agricultural by-products into marketable energy goods while creating local employment and reducing waste (Awoyale & Lokhat, 2019). A notable strength of Uganda's approach is its multi-stakeholder model. Local governments, NGOs, and donor agencies collaborate to facilitate user sensitization, technical training, and maintenance support, thereby enhancing both adoption rates and technology sustainability. This decentralized, participatory approach ensures that bioenergy projects are not only technically sound but also socially embedded and locally owned (Dahunsi et al., 2020).

Importantly, Uganda has extended bioenergy interventions to refugee-hosting districts, including Arua, Yumbe, and Adjumani, where the energy needs are acute due to rapid population growth and resource pressure. In these regions, community-based biogas systems, energy-efficient stoves, and briquette production enterprises have been introduced to promote environmental sustainability while offering refugees and host communities avenues for economic empowerment and skills development (Chukwuma et al., 2021b). Despite its successes, Uganda□s bioenergy sector faces several barriers. These include inconsistent supply chains, limited financing options, and weak quality assurance mechanisms. Moreover, while awareness of clean energy has grown, behavioral resistance and affordability challenges remain obstacles to large-scale diffusion, especially among the poorest households (Elum et al., 2017).

6. Innovations in Biomass Technologies

Recent advancements in biomass energy systems have introduced a range of technologies aimed at enhancing the efficiency, scalability, and environmental sustainability of biomass utilization. In Nigeria and Uganda, a number of context-specific innovations have emerged to transform traditional biomass practices into modern, renewable energy solutions. These innovations not only improve energy access but also contribute to climate mitigation and rural livelihoods.

6.1 Gasification and Pyrolysis Technologies

Gasification and pyrolysis represent cutting-edge thermal conversion methods that have garnered increasing attention in sub-Saharan Africa. These processes involve the decomposition of organic matter at high temperatures in the absence (or limited presence) of oxygen, resulting in the production of syngas (a mixture of carbon monoxide, hydrogen, and methane), bio-oil, and biochar. According to Balogun et al. (2018), gasification systems tailored for rural Nigerian settings have successfully leveraged locally available agricultural residues□such as cassava peels, sawdust, and plantain stems□as viable feedstocks. These materials, which are typically discarded or subjected to open burning, contribute significantly to environmental degradation and air pollution when unmanaged. By redirecting them into controlled gasification processes, rural communities are now exploring cleaner and more sustainable energy pathways.

The syngas produced through gasification is rich in carbon monoxide, hydrogen, and methane, making it a suitable fuel for internal combustion engines that can generate electricity at the microgrid or household scale. This decentralized model of energy production is particularly relevant in Nigeria, where national grid access remains limited, especially in rural areas. As Balogun et al. (2018) emphasize, these systems not only increase energy access but also enhance energy security and resilience, particularly in underserved and off-grid communities. Furthermore, the biochar by-product of the gasification process has garnered attention for its multiple co-benefits. When applied to agricultural soils, biochar improves soil structure, enhances water retention, and increases nutrient availability, thereby boosting crop yields. Additionally, biochar is recognized for its ability to sequester carbon, thus contributing to climate change mitigation by capturing atmospheric CO_2 in a stable form that remains in the soil for extended periods (Lehmann & Joseph, 2015). This positions gasification as not only an energy solution but also a key component in integrated agricultural and environmental management strategies.

Furthermore, small-scale pyrolysis units deployed in rural Nigeria have shown significant promise in converting locally available biomass such as cassava peels, plantain stems, and other agricultural residues into bio-oil and biochar, both of which have valuable end uses (Awoyale & Lokhat, 2019). The bio-oil, a liquid fuel derived from the thermal decomposition of biomass in the absence of oxygen, can serve as a viable alternative to kerosene for cooking and lighting, particularly in off-grid areas where access to conventional energy sources is limited or prohibitively expensive. This substitution not only reduces dependence on petroleum imports but also mitigates the health and environmental impacts associated with kerosene combustion, such as indoor air pollution and greenhouse gas emissions.

The biochar by-product produced during pyrolysis also plays a critical role in sustainable agriculture. It enhances soil fertility by improving nutrient retention, increasing microbial activity, and boosting water-holding capacity factors that are especially vital in Nigeria s degraded or nutrient-poor soils (Lehmann & Joseph, 2015). Additionally, biochar contributes to carbon sequestration, locking carbon in the soil for long periods and thereby offering a natural climate mitigation strategy. This dual outcome clean energy generation and agricultural productivity exemplifies the core tenets of the circular economy, where waste is transformed into resources that fuel broader socio-economic development. Moreover, pyrolysis technologies are often modular and scalable, making them adaptable to various rural contexts. They can be integrated into agro-processing value chains, utilizing residues from crop production and food processing. This integration creates opportunities for rural entrepreneurship, job creation, and community-led innovation. As Awoyale & Lokhat (2019) argue, such innovations are instrumental in advancing rural development, reducing energy poverty, and promoting environmental sustainability.

6.2 Biogas Digesters for Rural and Semi-Urban Households

Biogas technology has also evolved to suit the economic and spatial constraints of smallholder farmers and peri-urban households. Traditional biogas systems, which rely on anaerobic digestion of organic waste to produce methane-rich gas, have been modified into low-cost, modular digesters capable of using cow dung, poultry droppings, and kitchen waste. Dunmade et al. (2020) document several pilot biogas projects in northern Nigeria where small-scale anaerobic digesters were introduced on livestock farms as a means to address both energy scarcity and agricultural waste management. These biogas units, typically fed with cow dung and kitchen waste, have been tailored for low-income, rural households and smallholder farmers. The digesters produce methane-rich biogas, which is captured and used as a clean, renewable fuel for cooking offering a cost-effective and health-conscious alternative to traditional biomass fuels such as firewood and charcoal.

The adoption of biogas systems in these settings is particularly impactful because it tackles multiple development challenges simultaneously. First, the shift from wood-based fuels to biogas significantly reduces indoor air pollution, which is a leading cause of respiratory illnesses among women and children in rural Nigeria (World Health Organization, 2016). Second, the technology supports climate change mitigation by curbing methane emissions from unmanaged livestock waste and reducing deforestation for firewood collection (UNDP, 2019). Moreover, the digestate a nutrient-rich slurry left after anaerobic digestion serves as a valuable organic fertilizer, contributing to sustainable agricultural practices. When applied to farmlands, it enhances soil fertility, improves crop yields, and reduces the need for chemical fertilizers, which are often costly and environmentally harmful (Surendra et al., 2014). This reinforces a closed-loop agricultural system, aligning with the principles of integrated waste and resource management.

The success of these projects, as Dunmade et al. (2020) emphasize, depends on factors such as community training, technical support, and institutional backing. In cases where local farmers were involved in the design and operation of the digesters, uptake and maintenance levels were higher, highlighting the importance of participatory approaches in renewable energy interventions. However, widespread deployment is still hampered by limited awareness, inadequate financing mechanisms, and the absence of clear policy incentives for rural bioenergy development (Elum et al., 2017; Iloeje et al., 2020). Such innovations are particularly significant in Uganda, where the integration of biogas systems in refugee settlements and rural schools has yielded multifaceted socio-environmental benefits. As Chukwuma et al. (2021b) highlight, these biogas interventions not only provide a sustainable and localized energy source but also play a critical role in addressing gender-based energy burdens and public health challenges.

In many Ugandan rural communities and humanitarian settings, women and girls are traditionally responsible for sourcing firewood□a task that can consume several hours per day and expose them to risks such as physical strain, gender-based violence, and lost educational opportunities (FAO, 2017; UNHCR, 2020). The introduction of biogas systems alleviates these burdens by reducing dependence on fuelwood, thereby freeing up time for education, income-generating activities, and rest. In schools, biogas cooking facilities have also enhanced nutrition programs by enabling faster and safer food preparation, contributing to improved learning environments and attendance rates (GIZ, 2019). From an environmental perspective, biogas adoption helps combat deforestation and land degradation, especially in densely populated or ecologically fragile areas like refugee-hosting districts. By diverting organic waste such as animal manure and food residues into biodigesters, these systems reduce the volume of methane emissions that would otherwise result from open decomposition, contributing to climate change mitigation (Karekezi et al., 2012). Moreover, the by-product□bioslurry□is used as a low-cost organic fertilizer, enhancing agricultural productivity and promoting a circular economy in both host and refugee communities.

Government agencies, development partners, and local NGOs have been pivotal in facilitating these outcomes by providing technical training, subsidies for digester construction, and awareness campaigns aimed at fostering behavioral change (Awoyale & Lokhat, 2019). Successful models such as the Biogas for Better Life Program and the Green Heat Uganda Initiative illustrate the potential of scalable, community-centered bioenergy solutions when supported by institutional coordination and long-term policy commitment.

6.3 Bioethanol from Lignocellulosic Biomass

The production of bioethanol from cellulosic waste offers a promising avenue for fossil fuel substitution, especially for blending with gasoline or as a standalone fuel in ethanol stoves. Unlike traditional ethanol production methods that rely on sugar-rich crops (e.g., sugarcane), advanced methods now utilize lignocellulosic materials such as maize stalks, rice straw, and sorghum residues□feedstocks that are abundant but often discarded. Awoyale and Lokhat (2019) note that enzymatic hydrolysis and fermentation techniques have been successfully adapted to the local agricultural and technological contexts in Nigeria, enabling the conversion of lignocellulosic biomass□such as maize stalks, cassava peels, sugarcane bagasse, and rice husks□into bioethanol. These processes rely on cellulolytic enzymes to break down the cellulose and hemicellulose components of plant biomass into fermentable sugars, which are subsequently converted into ethanol through microbial fermentation, typically using Saccharomyces cerevisiae (Rana et al., 2012; Awoyale & Lokhat, 2019).

What makes these innovations particularly impactful in the Nigerian context is their low energy requirement and cost-effectiveness, especially when compared to first-generation ethanol production systems that rely on food crops like corn or sugarcane. Experimental setups and pilot plants established in agricultural zones have demonstrated ethanol yields of up to 200 liters per tonne of dry biomass, depending on feedstock composition and process optimization (Balogun et al., 2018). These yields indicate the scalability and replicability of cellulosic ethanol systems, especially in rural areas where agricultural residues are abundant but often wasted or burned. Moreover, the adoption of such technologies aligns with the circular economy model, offering dual benefits of waste valorization and clean energy production. If scaled effectively, bioethanol could serve as a viable alternative to kerosene and petrol, especially for domestic cooking and small engine use, thereby reducing fossil fuel dependence and mitigating indoor air pollution (Dunmade et al., 2020; Elum et al., 2017). This innovation addresses multiple challenges simultaneously: it reduces agricultural waste, lowers greenhouse gas emissions, and offers cleaner alternatives to traditional fuels such as kerosene and charcoal. The utilization of agricultural residues□previously discarded or openly burned□into ethanol not only minimizes environmental pollution but also contributes to climate change mitigation by displacing fossil fuels with a renewable energy source (Awoyale & Lokhat, 2019; Balogun et al., 2018). Additionally, the shift from kerosene and charcoal to ethanol-based fuels significantly improves indoor air quality, which is particularly beneficial for women and children in rural households, where the health burden from smoke inhalation is disproportionately high (Elum et al., 2017).

As local ethanol production matures, its relevance extends beyond household energy needs to support a broader range of industrial applications. In the pharmaceutical and cosmetic sectors, ethanol is a critical solvent and disinfectant, while in the transport sector, it can be blended with petrol to create biofuels like E10 or E20, contributing to fuel security and reduced carbon intensity in transportation (Dunmade et al., 2020; IEA, 2022). The development of local ethanol value chains can stimulate job creation, encourage technology transfer, and promote rural industrialization, thereby laying the foundation for a diversified bioeconomy. Furthermore, this aligns with regional and global sustainability goals, including the Sustainable Development Goals (SDGs)□notably SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action). However, realizing this potential requires the establishment of supportive institutional frameworks, including fiscal incentives, feed-in tariffs, and subsidies for clean energy startups, as well as continued investment in research and development to improve efficiency and scalability (Dahunsi et al., 2020).

7. Challenges and Barriers

Despite the growing interest in bioenergy as a sustainable solution to energy poverty and environmental degradation, several critical challenges continue to impede its large-scale deployment in sub-Saharan Africa, particularly in Nigeria and Uganda.

- **Infrastructure Deficits**
  A major constraint lies in the weak rural infrastructure, especially road networks and energy transmission systems. Poor transportation infrastructure hampers the efficient collection and distribution of biomass feedstocks, increasing logistics costs and limiting access to remote communities where bioenergy is most needed (Dahunsi et al., 2020). Additionally, the absence of grid extension in many rural areas undermines opportunities for grid-connected bioenergy projects, leaving off-grid solutions as the only viable□yet often underfunded□option.

- **Financial Constraints**
  Bioenergy technologies typically require substantial initial investments, which are unaffordable for most low-income households and smallholder farmers. The high capital costs associated with biogas digesters, pyrolysis units, and ethanol production systems discourage uptake, especially in regions without credit facilities or financial incentives. Moreover, limited access to microfinance, poor investor confidence, and underdeveloped financial markets restrict the flow of private capital into the sector (Awoyale & Lokhat, 2019). This lack of financing mechanisms significantly slows down commercialization and innovation diffusion.

- **Policy and Institutional Gaps**
  Fragmentation across sectors further complicates bioenergy development. Coordination failures among energy, agriculture, environment, and local governance institutions result in duplicative efforts and policy inconsistencies. For instance, while energy ministries may promote renewable technologies, agricultural agencies often neglect the potential of crop residues as energy sources. The absence of harmonized standards, supportive tariffs, and bioenergy-specific regulations creates a disincentive for investment and scale-up (Elum et al., 2017; Chukwuma et al., 2021a).

- **Sociocultural Factors**
  Sociocultural resistance also plays a significant role in shaping adoption rates. In many rural communities, traditional cooking methods are deeply embedded in daily life, and attempts to introduce alternative fuels or stoves often meet with skepticism. Gender dynamics exacerbate this barrier, as women□who are primary users of household energy□may lack decision-making power over technology adoption or face constraints in accessing training and maintenance support (Dunmade et al., 2020). Sensitization campaigns and participatory implementation strategies are essential to overcome these deeply rooted norms and promote behavioral change.

8. Policy Implications

Addressing energy poverty through biomass innovations in sub-Saharan Africa, particularly in Nigeria and Uganda, requires proactive and inclusive policy responses. Given the dual challenge of environmental sustainability and energy access, targeted interventions must bridge gaps in governance, financing, technology deployment, and community participation. The following strategies are crucial:

Integrate Bioenergy into National Rural Electrification Plans

To maximize the impact of biomass technologies, bioenergy must be explicitly integrated into national electrification frameworks. This includes aligning bioenergy initiatives with rural energy access goals under policies like Nigeria□s NREEEP (2015) and Uganda□s Renewable Energy Policy (2007). Governments should identify bioenergy potential zones, incorporate decentralized systems into energy master plans, and adopt spatial energy mapping to optimize biomass use at the local level (Dahunsi et al., 2020).

Establish Microfinance Schemes and Community Cooperatives

Financing remains a critical barrier to bioenergy adoption. Policymakers should support the creation of rural microfinance institutions, energy cooperatives, and revolving loan funds tailored to low-income households. These financial models can enable shared ownership of bioenergy systems, particularly among women and smallholder farmers, while reducing risk and improving repayment rates (Awoyale & Lokhat, 2019). Cooperatives can also facilitate bulk procurement, user training, and maintenance support, thereby improving project sustainability.

Provide Incentives and Subsidies for Locally Manufactured Bioenergy Systems

Local manufacturing and assembly of biomass technologies can reduce costs and stimulate job creation. To support this, governments should offer tax relief, subsidies, or import duty waivers on components required for biogas digesters, gasifiers, and cookstoves. In parallel, local innovation hubs and vocational training centers can help develop technical capacity and promote standardized production of bioenergy systems (Elum et al., 2017). Targeted subsidies, especially for first-time users in remote areas, can catalyze early adoption and market formation.

Encourage Public-Private Partnerships for Research, Development, and Deployment

Public-private partnerships (PPPs) are essential to scale up bioenergy innovation. Governments should create enabling environments□through regulatory clarity, risk guarantees, and access to public lands□that attract private investment into the sector. Collaborations between research institutions, NGOs, and the private sector can also drive the development of context-specific technologies, such as low-cost pyrolysis units or modular biogas systems (Balogun et al., 2018). Additionally, PPPs can support monitoring and evaluation frameworks that inform adaptive policy and improve impact tracking.

Promote Gender-Responsive and Inclusive Policies

Given the gendered nature of energy use, policies must consider the needs and contributions of women in biomass energy value chains. This includes involving women in decision-making, supporting women-led enterprises, and ensuring access to training and financing. Inclusive policies will not only enhance adoption rates but also contribute to broader development goals, including health, education, and women□s economic empowerment (Chukwuma et al., 2021b).

9. Conclusion and Future Directions

Biomass and bioenergy innovations represent viable and scalable pathways to addressing energy poverty in rural Africa, particularly in contexts where centralized grid expansion remains economically and logistically challenging. When effectively harnessed, biomass resources can contribute not only to energy access but also to environmental sustainability, rural livelihoods, and gender equity. The integration of bioenergy technologies□such as gasification, pyrolysis, biogas digesters, and cellulosic ethanol production□demonstrates promising co-benefits including waste management, emissions reduction, and agricultural productivity. To realize this potential, it is imperative that technology deployment is guided by the principles of energy justice, ensuring equitable access, community ownership, and socio-cultural appropriateness. Strategic policy support, cross-sectoral coordination, and investment in local innovation ecosystems will be critical to scaling impact.

Future research should focus on emerging areas with high transformative potential. These include the development of regional biomass value chains and cross-border trade mechanisms, comprehensive life-cycle assessments comparing biomass with fossil and other renewables, and the integration of digital technologies□such as remote sensing, IoT, and AI□for monitoring, optimization, and predictive maintenance of bioenergy systems.

References

Amoo, O. M., & Fagbenle, R. L. (2013). Renewable municipal solid waste pathways for energy generation and sustainable development in the Nigerian context. International Journal of Energy and Environmental Engineering, 4(1). https://doi.org/10.1186/2251-6832-4-1

Anyaoha, K. E., & Zhang, L. (2021). Renewable energy for environmental protection: Life cycle inventory of Nigeria□s palm oil production. Resources, Conservation and Recycling, 174, 105797. https://doi.org/10.1016/j.resconrec.2021.105797

Awoyale, A. A., & Lokhat, D. (2019). Harnessing the potential of bio-ethanol production from lignocellulosic biomass in Nigeria □ A review. Biofuels, Bioproducts and Biorefining, 13(1), 192□207. https://doi.org/10.1002/bbb.195

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2017). Life cycle assessment of waste-to-energy (WtE) technologies for electricity generation using municipal solid waste in Nigeria. Applied Energy, 201, 200□218. https://doi.org/10.1016/j.apenergy.2017.05.054

Ayodele, T. R., Ogunjuyigbe, A. S. O., & Alao, M. A. (2018). Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. Journal of Cleaner Production, 203, 718□735. https://doi.org/10.1016/j.jclepro.2018.08.275

Balogun, A. O., Lasode, O. A., & McDonald, A. G. (2018). Thermochemical and pyrolytic analyses of Musa spp. residues from the rainforest belt of Nigeria. Environmental Progress & Sustainable Energy, 37(6), 1932□1941. https://doi.org/10.1002/ep.12958

Bappah, M., Bradna, J., Velebil, J., & Malatak, J. (2019). The potential of energy recovery from by-products of small agricultural farms in Nigeria. Agronomy Research, 17(6), 2180□2186.

Ben-Iwo, J., Manovic, V., & Longhurst, P. (2016). Biomass resources and biofuels potential for the production of transportation fuels in Nigeria. Renewable and Sustainable Energy Reviews, 63, 172□192. https://doi.org/10.1016/j.rser.2016.05.050

Chukwuma, E. C., Ojediran, J. O., Anizoba, D. C., Ubah, J. I., & Nwachukwu, C. P. (2021a). Geospatially based analysis and economic feasibility evaluation of waste to energy facilities: A case study of local government areas of Anambra State of Nigeria. Biomass Conversion and Biorefinery, 1□12. https://doi.org/10.1007/s13399-021-01484-5

Chukwuma, E. C., Okey-Onyesolu, F. C., Ani, K. A., & Nwanna, E. C. (2021b). GIS bio-waste assessment and suitability analysis for biogas power plant: A case study of Anambra State of Nigeria. Renewable Energy, 163, 1182□1194. https://doi.org/10.1016/j.renene.2020.09.040

Dahunsi, S. O., Fagbele, O. O., & Yusuf, E. O. (2020). Bioenergy technologies adoption in Africa: A review of past and current status. Journal of Cleaner Production, 264, 121715. https://doi.org/10.1016/j.jclepro.2020.121715

Deenanath, E. D., Iyuke, S., & Rumbold, K. (2012). The bioethanol industry in sub-Saharan Africa: History, challenges and prospects. Journal of Biomedicine and Biotechnology, 416491. https://doi.org/10.1155/2012/416491

Dunmade, I. S., Akinlabi, E., & Daramola, M. (2020). A sustainable approach to boosting liquid biofuels production from second generation biomass resources in West Africa. Agronomy Research, 18, 109□121. https://doi.org/10.15159/AR.20.109

EEA □ European Environment Agency. (2021). Diversion of waste from landfill in Europe. Retrieved July 27, 2022, from https://www.eea.europa.eu/ims/diversion-of-waste-from-landfill

Elum, Z. A., Modise, D. M., & Nhamo, G. (2017). Climate change mitigation: The potential of agriculture as a renewable energy source in Nigeria. Environmental Science and Pollution Research, 24(4), 3260□3273. https://doi.org/10.1007/s11356-016-8060-3

Ezealigo, U. S., Ezealigo, B. N., Kemausuor, F., Achenie, L. E. K., & Onwualu, A. P. (2021). Biomass valorization to bioenergy: Assessment of biomass residues□ availability and bioenergy potential in Nigeria. Sustainability, 13(24), 13806. https://doi.org/10.3390/su132413806

Federal Republic of Nigeria, Ministry of Power. (2015). National Renewable Energy and Energy Efficiency Policy (NREEEP). http://admin.theiguides.org/Media/Documents/NREEE%20POLICY%202015-%20FEC%20APPROVED%20COPY.pdf

Gatete, C., & Dabat, M. H. (2017). From the fuel versus food controversy to the institutional vacuum in biofuel policies: Evidence from West African. Energy, Sustainability and Society, 7, 1□17. https://doi.org/10.1186/s13705-017-0127-2

GBN □ Ghana Business News. (2017, January 18). Local company announces production of ethanol from cassava. Retrieved July 10, 2022, from https://www.ghanabusinessnews.com/2017/01/18/local-company-announces-production-of-ethanol-from-cassava/

Giwa, A., Alabi, A., Yusuf, A., & Olukan, T. (2017). A comprehensive review on biomass and solar energy for sustainable energy generation in Nigeria. Renewable and Sustainable Energy Reviews, 69, 620–641. https://doi.org/10.1016/j.rser.2016.11.160

Hoornweg, D., & Bhada-Tata, P. (2012). What a waste: A global review of solid waste management (Urban Development Series Knowledge Papers No. 15, pp. 1–98). World Bank. https://openknowledge.worldbank.org/handle/10986/17388

Ibikunle, R. A., Titiladunayo, I. F., Akinnuli, B. O., Lukman, A. F., Ikubanni, P. P., & Agboola, O. O. (2018). Modelling the energy content of municipal solid waste and determination of its physicochemical correlation, using multiple regression analysis. International Journal of Mechanical Engineering and Technology, 9(11), 220–232.

Ibikunle, R. A., Titiladunayo, I. F., Akinnuli, B. O., Dahunsi, S. O., & Olayanju, T. M. A. (2019). Estimation of power generation from municipal solid wastes: A case study of Ilorin metropolis, Nigeria. Energy Reporyts, 5, 126–135. https://doi.org/10.1016/j.egyr.2019.01.007

Matemilola, S., Elegbede, I. O., Kies, F., Yusuf, G. A., & Yangni, G. M. (2019). An analysis of the impacts of bioenergy development on food security in Nigeria: Challenges and prospects. Environmental and Climate Technologies, 23(1), 64–83.

McCulloch, N., Moerenhout, T., & Yang, J. (2021). Fuel subsidy reform and the social contract in Nigeria: A micro-economic analysis. Energy Policy, 156, 112336.

Mohammed, Y. S., Mustafa, M. W., Bashir, N., & Mokhtar, A. S. (2013). Renewable energy resources for distributed power generation in Nigeria: A review of the potential. Renewable and Sustainable Energy Reviews, 22, 257–268.

Mohammed, Y. S., Mustafa, M. W., Bashir, N., Ogundola, M. A., & Umar, U. (2014). Sustainable potential of bioenergy resources for distributed power generation development in Nigeria. Renewable and Sustainable Energy Reviews, 34, 361–370.