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BIOMASS RESOURCE ASSESSMENT USING THE INVENTORY APPROACH FOR BIOFUEL PRODUCTION POTENTIAL IN EDO STATE, NIGERIA

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ABSTRACT

Biomass resources present a vast, untapped potential for sustainable energy production in Nigeria. This study uses an inventory approach to evaluate the availability and suitability of biomass resources in Edo State for biofuel production. It identifies the types, quantities, and spatial distribution of biomass resources, focusing on agricultural, forest, urban, and other wastes. Solid biomass and waste constitute about 80% of Nigeria's total primary energy consumption. The research assesses biomass feedstocks for first to fourth-generation biofuels, exploring their viability for bioethanol, biodiesel, and biogas production. Emerging biofuel projects in Nigeria predominantly depend on first-generation feedstocks, primarily food crops, which could create conflicts between food and energy needs. This study highlights the importance of shifting focus to non-food biomass resources, including agricultural residues and organic waste. Preliminary findings reveal that Edo State possesses significant potential for biofuel production, supported by favorable agro-ecological conditions and extensive crop cultivation. However, challenges such as insufficient infrastructure, limited access to modern agricultural technologies, and policy gaps hinder progress. The study provides crucial insights for policymakers, researchers, and investors, emphasizing the sustainable utilization of biomass resources for renewable energy production. Addressing identified challenges could unlock the Edo State's biomass potential, enhancing energy diversification and contributing to sustainable development. The results aim to guide optimized biomass resource utilization, promoting biofuel as a viable solution for Nigeria's energy and environmental challenges.

1. INTRODUCTION

The combustion of fossil fuels, including coal, oil, and natural gas, has dominated global energy production for decades (Andres et al., 2012). The use of fossil fuels as primary energy is a major global concern due to its substantial contribution to greenhouse gas (GHG) emissions, particularly carbon dioxide (CO_2), which is a leading driver of climate change. The release of CO_2 during fossil fuel combustion exacerbates global warming, resulting in severe environmental impacts. Fossil fuels contribute approximately 23% of global CO_2 emissions (Saboori et al., 2013), emphasizing the urgent necessity for transitioning to cleaner energy sources to meet international climate goals, such as those outlined in the Paris Agreement.

While Sub-Saharan Africa contributes less than 4% of global CO_2 emissions (IRENA, 2023), the region faces disproportionate risks from climate change. Rising temperatures, erratic rainfall, desertification, and extreme weather events threaten livelihoods dependent on agriculture and natural resource extraction (IPCC, 2023; Climate Analytics, 2024; IMF, 2024). Nigeria, as Africa's largest economy, exemplifies the challenges of balancing economic growth with environmental sustainability. Fossil fuels dominate the country's energy mix, accounting for over 80% of energy production and approximately 59.5% of total CO_2 emissions (Tajudeen et al., 2015). With rapid population growth, urbanization, and industrialization, Nigeria faces mounting environmental challenges, including rising GHG emissions, deforestation, and pollution.

The Federal Republic of Nigerian has recently pledged to achieve net-zero emissions by 2060, necessitating a transition to renewable energy sources. Among these, biomass stands out as a promising alternative. Derived from organic materials such as agricultural residues, forestry by-products, and municipal waste, biomass offers a sustainable pathway for producing electricity, heat, and biofuels like biodiesel, bioethanol, and biogas (Fan et al., 2021; Kumar et al., 2023).

The global energy crisis and climate change emphasize the need to transition away from fossil fuels. Sustainable energy solutions are required to reduce environmental damage while improving energy security and fostering economic growth (IPCC, 2021). Among renewable energy options, biomass stands out as a promising alternative. Biomass, derived from agricultural residues, forestry by-products, and municipal waste, provides a sustainable way to generate electricity, heat, and biofuels such as bioethanol, biodiesel, and biogas (López et al., 2020; Balat, 2011). Biomass can reduce CO_2 emissions, enhance energy security, and diversify the energy mix (Chen et al., 2020) and fosters rural economic development.

Despite its potential, there are significant challenges in fully utilizing biomass in Sub-Saharan Africa. One of the key barriers is the lack of comprehensive biomass inventories that assess the availability and types of biomass resources. Effective biomass utilization depends on resource assessments that measure the quantity and quality of available biomass. Currently, biomass resource assessments use two main approaches: the inventory approach, which estimates physical quantities, and the economic approach, which considers price factors. However, the absence of international standards complicates the development of standardized data, hindering biomass optimization.

Improving biomass characterization and resource assessment techniques is crucial for enhancing biomass conversion technologies and ensuring efficient utilization. Accurate biomass inventories are essential for informing policy decisions and guiding investments in bioenergy infrastructure. Moreover, better inventory systems are needed to explore the full potential of biofuels like bioethanol, biodiesel, and biogas, which remain underdeveloped in many African countries (Demirbas, 2009).

Biomass offers significant potential for renewable energy production and environmental sustainability. By focusing on detailed biomass resource inventories, Nigeria and Sub-Saharan Africa can unlock the potential of biofuels, contributing to energy transition goals. Biomass from agricultural residues, forestry by-products, and organic waste can replace fossil fuels, addressing energy poverty in rural areas, promoting economic development, and reducing environmental degradation. Investing in cleaner energy technologies and optimizing biomass utilization will foster sustainable growth, improve energy security, and support global climate goals.

The aim of this study is to assess the biomass resources available in Edo State, Nigeria, and evaluate their potential for biofuel production, with a focus on bioethanol, biodiesel, and biogas. The study aims to identify and explore the feasibility of utilizing first, second, third, and fourth-generation biomass feedstock, including agricultural residues, energy crops, and organic waste. It seeks to examine the opportunities for integrating non-food biomass resources into existing petroleum refinery infrastructure to co-process biofuels, thereby addressing the food-versus-fuel conflict. Additionally, the study aims to evaluate the current biomass conversion technologies in Nigeria, assess their readiness for large-scale application, and provide actionable insights for policymakers, researchers, and investors to foster sustainable bioenergy development in Edo State and contribute to Nigeria's energy security, sustainable agricultural practices, and greenhouse gas emission reduction goals.

2. LITERATURE SURVEY

Energy plays a pivotal role in national development and economic expansion, and its significance cannot be overstated. Human progress, economic growth, and societal well-being rely heavily on the adequate, secure, and efficient provision of energy Abdallah et al., (2015). According to Lior (2011), patterns of energy use are closely linked to environmental quality and to essential resources such as water and food. In a related argument, Lior (2011) emphasized that Africa's energy sector requires urgent attention and strategic development to enhance citizens' quality of life and potentially supply energy to the global market.

The ongoing global energy crisis, compounded by the escalating threat of climate change, has intensified the need to shift away from heavy dependence on fossil fuels. Without alternative energy sources, shortages will persist and environmental degradation will worsen. Renewable and sustainable energy options—such as wind, solar, biomass, hydropower, ocean energy, and geothermal—are therefore being actively explored, each with distinct advantages and limitations. Abolhosseini et al. (2014) identified energy security, economic benefits, and reductions in carbon emissions as the principal drivers behind growing interest in renewable energy technologies.

Developing nations appear particularly vulnerable to the global energy crisis. Their economies are highly sensitive to fluctuations in energy markets due to excessive dependence on non-renewable energy sources and limited capacity to maintain stable and affordable energy supplies Hussain et al. (2019). Yet many developing countries, including Nigeria, possess abundant and largely untapped renewable resources with significant potential applications (Ismail et al., 2014; Orisaleye et al., 2018; Ismail et al., 2013; Orisaleye et al., 2018). As noted by Piebalgs (2007), these countries are well positioned to expand renewable energy use given their ample resources—ranging from wind and solar to biomass, geothermal, and hydropower—although political and financial support may be required. Evidence further shows that renewable energy contributes positively to economic development and employment generation and supports environmental sustainability while enhancing energy self-sufficiency ((Osiolo et al., 2016; Tun et al, 2019).

Evans et al. (2009) evaluated the social impacts of renewable energy systems and ranked them using sustainability indicators. Their findings placed wind energy as the most sustainable option, followed by hydropower, solar photovoltaics, and geothermal. Mas'ud et al (2015), in assessing renewable energy readiness in Nigeria and Cameroon, reported high solar radiation levels and viable wind speeds in both countries. They also highlighted Africa's substantial energy potential, which could stimulate economic growth and meet future electricity demand. However, Ajayi (2009) observed that the diffusion of renewable technologies is hindered by challenges such as limited awareness and inadequate technical capacity.

Many developing nations—particularly in sub-Saharan Africa—possess vast arable land and rely heavily on agriculture, making biomass an abundant energy source. However, biomass is often used in inefficient or environmentally damaging ways. Despite these drawbacks, biomass still accounts for roughly 70% of total energy consumption in some countries Keles et al (2017). Keles et al (2017) estimate that by 2030 approximately 823 million Africans will depend on biomass for cooking and heating. In response, Gujba et al (2015) recommend prioritising the deployment of advanced cookstoves to mitigate indoor air pollution and relieve pressure on biomass supplies.

Global concern over climate change has led the United Nations to convene numerous conferences and summits focused on climate mitigation. These events have yielded major international agreements on greenhouse gas reduction. The Kyoto Protocol of 1997 (COP3) formally acknowledged anthropogenic CO_2 emissions as a key contributor to global warming and established differentiated responsibilities for emissions reduction based on countries' capacities and levels of development Gribb et al (2004). The Paris Agreement adopted at COP21 in 2015 set the strategic direction for post-2020 climate action, recognizing the need to achieve net-zero emissions by 2050 to constrain global warming to 1.5 °C—a threshold considered socially and economically safer Summit (2019). Subsequent meetings, such as COP25 in Madrid (2019), sought to clarify operative rules for the Paris Agreement and encouraged nations to submit strengthened climate action plans despite disagreements over certain implementation mechanisms (KPMG, 2019).

Abolhosseini et al. (2014) argue that the two most effective approaches to lowering CO_2 emissions and mitigating climate change are large-scale replacement of fossil fuels with renewable energy and significant improvements in energy efficiency. Nevertheless, Keles et al (2017) caution that robust and reliable data remain insufficient for effective biomass energy planning or policy formulation. As such, proper management and sustainable utilization of biomass resources are essential to maximize their role in energy production.

Against this background, the present study identifies viable biomass resources available in Nigeria and evaluates the technologies suitable for their conversion into bioenergy. It further estimates both the theoretical and technical potentials of these resources and reviews existing Nigerian policy measures aimed at promoting biomass-based energy development.

3. MATERIALS AND METHODS

3.1 Study area

Edo State, located in southern Nigeria, covers an area of 19,840 km² and consists of 18 Local Government Areas (LGAs) fig 1. It lies between 5° 5′N and 7° 35′N latitudes, and 5°E and 6° 40′E longitudes, bordered by Kogi and Ondo States to the west, Delta and Kogi States to the east, and Delta State to the south (Azeez et al., 2010). The state has a tropical climate with distinct wet (March–October) and dry (November–March) seasons. The landscape is predominantly low-lying, with the northern region characterized by hills rising to about 672 meters above sea level. Edo State is rich in natural resources, particularly its forests, with over 22 reserves housing valuable species like Afara, Mahogany, and Albizia (Kalu and Ilavbarhe, 2010). These forests support logging, lumbering, and farming, providing significant income for local communities (Balogun and Iyekekpolor, 2020). The state's biomass resources offer potential for sustainable energy development.

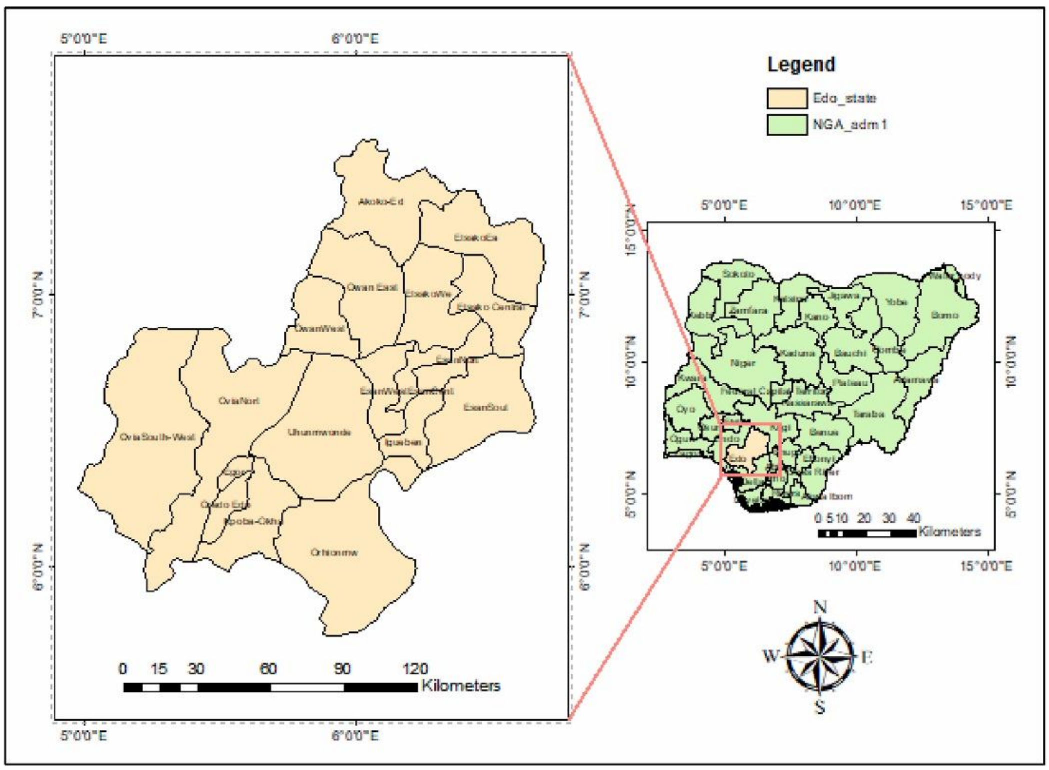

Figure 1. Map of Edo State, showing the 18 Local Government Areas and highlighting its geographical features

3.2 Field Surveys

Field surveys were systematically designed to capture the availability and diversity of biomass resources across Edo State, encompassing agricultural farms, forestry operations, and municipal waste sites. The state was divided into distinct zones based on agricultural practices, land use patterns, and industrial activities to ensure comprehensive coverage of biomass sources. Within each zone, specific locations such as crop fields, sawmills, and landfill sites were selected for sampling based on their potential biomass yield. Surveys were conducted during different agricultural seasons to account for seasonal variations in biomass availability. At each site, biomass samples, including crop residues like maize stalks, rice husks, and cassava peels, were carefully collected and cataloged. Forestry by-products such as sawdust and wood offcuts were sourced from logging and sawmill operations, while organic waste was gathered from municipal dumpsites and composting facilities. Detailed documentation was maintained, including the source, quantity, and condition of biomass.

3.3 Interviews

Structured interviews were conducted with key stakeholders, including farmers, forestry operators, municipal officials, and industry stakeholders, to gather qualitative and quantitative data on biomass availability and utilization. Farmers were interviewed to estimate the volume of crop residues produced and understand current practices for disposal or reuse, such as burning, composting, or feeding to livestock. Forestry operators provided insights into the types and quantities of residues generated from logging and sawmill activities. Municipal officials were consulted to assess the volume of organic waste collected, collection rates, and waste management practices in urban and peri-urban areas. Industry stakeholders, such as bioenergy companies and agricultural cooperatives, were engaged to explore existing biomass supply chains and demand for feedstocks. Interviews followed a structured format, starting with background questions about the respondent's operations, followed by in-depth questions on biomass generation, current usage practices, and barriers to efficient utilization. The interview data were cross verified with field observations and secondary sources to ensure consistency and reliability.

3.4 Direct Measurements

Direct measurements were performed to quantify biomass feedstocks and evaluate their potential for biofuel production using standardized sampling and analytical techniques. For agricultural residues, a representative portion of the collected material was weighed in its fresh state, then air-dried to a constant weight to determine dry matter content. Wood residues, including sawdust and wood chips, were measured volumetrically, and samples were analyzed to determine their moisture content. Municipal organic waste was sorted to separate biodegradable components, which were weighed and characterized to assess their suitability for biofuel production. Proximate analysis was conducted on all biomass samples to determine key properties such as moisture content, ash content, volatile matter, and fixed carbon using standard laboratory equipment like muffle furnaces. Additionally, the calorific value of the biomass was measured using a bomb calorimeter to estimate its energy potential. Bulk density measurements were conducted to evaluate the logistical feasibility of storage and transportation. All measurements followed international standards such as ASTM D1762, ensuring accuracy and comparability of results. Samples were appropriately labeled and stored to prevent contamination or degradation before analysis.

4. RESULTS

The biomass resource inventory conducted in Edo State revealed significant potential for biofuel production from a variety of biomass feedstocks, including agricultural, forest, urban, and other organic wastes. Edo State's agro-ecological zones, comprising the Rainforest, Derived Savanna, Freshwater Swamp, and Floodplain zones, offer a diverse range of climatic and soil conditions that support the cultivation of various crops such as oil palm, cassava, rice, and maize, while also enabling sustainable agricultural practices and biodiversity conservation.

4.1 Agro-Ecological Zones of Edo State

The state's agro-ecology is defined by varying climatic and vegetative zones that influence the types of crops grown, the productivity of its land, and the agricultural practices employed. These agro-ecological zones are crucial in understanding the potential for biomass resource development and biofuel production, as the state's diverse climatic conditions provide a wide range of possibilities for cultivating various biomass feedstocks. The State spans across different climatic zones, from the humid tropical zones in the south to areas with relatively moderate rainfall in the north (Table 1). These variations in climate, rainfall patterns, and temperature influence the vegetation types, and subsequently, the types of crops that can thrive in different parts of the state. Edo State has three primary climatic zones: the Humid Tropical Zone in the south, characterized by high rainfall (2000-3000 mm) suitable for cash crops like cocoa, cassava, and oil palm; the Sub-Humid Zone in the central and northern regions, with moderate rainfall (1,200-2000 mm) ideal for crops such as maize, rice, and energy crops like sweet sorghum; and the Forest-Savannah Transition Zone, where forest and savannah vegetation overlap, supporting a variety of crops including tropical fruits, shrubs, and grasses for livestock grazing. These zones provide diverse agricultural opportunities, particularly for biofuel production.

4.1.1Biomass Resource Inventory in Edo State

Edo State's diverse agro-ecological zones play a crucial role in determining the types of crops cultivated and the availability of biomass resources. These resources serve as key feedstocks for biofuel production, offering immense potential to bolster the state's renewable energy sector. This inventory examines the biomass feedstocks available across the agro-ecological zones, including agricultural biomass, energy crops, forestry by-products, and urban biomass, highlighting their contributions to Edo State's bioenergy potential (Tables 2, 3, 4, and 5).

The rich agricultural diversity, with energy crops such as oil palm, cassava, sugarcane, maize, plantain, groundnut (peanut), soybean, and Jatropha are widely cultivated across its zones. These crops form an integral part of the production of bioethanol, biodiesel, and biogas, underscoring their importance in enhancing the state's renewable energy capabilities. Fertile soils and favorable climatic conditions (Table 1) support the large-scale cultivation of these high-yield crops, making agricultural biomass a cornerstone of Edo State's biofuel potential.

Edo State also benefits significantly from its extensive forest resources, particularly within the forest-savannah transition zone. This area provides a vast, untapped reservoir of biomass, including wood, sawdust, and other forestry by-products, which are suitable for renewable energy production. These resources enhance the state's capacity to generate bioenergy and reduce dependence on fossil fuels, presenting opportunities for large-scale and sustainable biofuel production.

The growing urban centres of Edo State generate considerable amounts of organic waste, such as food waste, yard waste, and municipal solid waste (MSW). This urban biomass represents a substantial resource for biofuel production via anaerobic digestion, a process that converts organic material into biogas. By establishing waste-to-energy facilities in urban areas, Edo State can address waste management challenges while simultaneously producing renewable energy for applications such as cooking, electricity, and heating. This dual-purpose approach promotes environmental sustainability and energy self-reliance.

Table 1. Summarizing The Agro-Ecological Zones of Edo State

Agro-Ecological Zone	Description	Location	Characteristics	Agricultural Activities	Soil Type	Economic Significance
Rainforest Zone	Dense vegetation, high rainfall, and biodiversity.	Southern and central parts of the state	- High annual rainfall (2000–3000 mm) - Humid climate, well-drained soils	- Crops: Cocoa, rubber, oil palm, yam, cassava, plantain, maize - Livestock: Small-scale poultry, goat, sheep farming	- Deep, well-drained soils - Rich in organic matter	- Plantation agriculture (cash crops) - Forest conservation
Derived Savanna Zone	Transitional zone with a mix of forest and grassland vegetation.	Northern parts of the state	- Transitional vegetation - Moderate rainfall (1200–2000 mm) - Grassland with scattered trees	- Crops: Maize, yam, cassava, guinea corn, millet, cowpea - Livestock: Cattle rearing, poultry farming	- Loamy to sandy soils - Moderate fertility	- Suited for mechanized and large-scale farming - Agro-industrial potential
Freshwater Swamp Zone	Low-lying areas prone to waterlogging, close to rivers and wetlands.	Along floodplains of rivers (e.g., Niger)	- High rainfall (2000–2500 mm) - High humidity - Periodic flooding - Waterlogged soils rich in organic matter - Vegetation: Mangroves, swamp forests	- Crops: Rice, sugarcane, vegetables - Fisheries: Aquaculture, artisanal fishing	- Waterlogged soils - Acidic and peaty soils	- Supports flood-tolerant crop farming - Key area for fisheries and biodiversity conservation
Mangrove Forest Zone	Riverine areas, characterized by periodic flooding and rich alluvial deposits.	Southernmost areas (coastal/estuarine regions)	- Seasonal flooding - Moderate to high rainfall - Brackish water ecosystem - High humidity - Saline soils	- Limited farming due to salinity - Fisheries: Shrimp and fish farming	- Alluvial soils - High fertility	- Crucial for fisheries and ecological balance - Potential for eco-tourism and mangrove restoration

Agricultural residues (Table 4) further augment Edo State's biomass resource inventory. Key crops like oil palm, cassava, maize, pineapples, rice, plantain, and groundnut yield significant amounts of residues, including fronds, peels, husks, and stalks. Annually, these residues amount to approximately 1–1.5 million tons, presenting opportunities for diverse applications such as biomass energy production, biogas generation, and the creation of organic fertilizers. However, realizing the full potential of these resources requires addressing challenges such as inefficient collection systems, inadequate infrastructure, and post-harvest losses. Overcoming these barriers will enable Edo State to maximize its renewable energy potential while contributing to sustainable waste management and recycling initiatives.

4.1.2 Inventory of Aquatic Weeds for Biofuels Production in Edo State

The study on aquatic weeds for biofuels production in Edo State reveals significant biomass availability across different regions, highlighting their potential for renewable energy generation (Table 6). The Benin River Basin, with over 12,000 tons of water hyacinth annually, represents the highest biomass density, capable of producing up to 1,500 cubic meters of methane per ton of dry biomass through biogas conversion. The Esan Region, characterized by duckweed and cattails, contributes about 8,000 tons of biomass annually, with a bioethanol yield of estimated values of 400 liters per ton. In Orhionmwon wetlands, approximately 6,000 tons of reeds and cattails are available for bioethanol and biochar production. Coastal areas in Ovia North support algae with 25-30% lipid content, offering a biodiesel output of about 2,000 liters per ton. Collectively, Edo State may generate approximately 26,000 tons of aquatic weed biomass annually, suitable for producing 10,000 cubic meters of biogas, 10,400 liters of bioethanol, and 5,200 liters of biodiesel. These findings demonstrate the potential of aquatic weeds to contribute to energy diversification and environmental sustainability in Edo State.

4.1.3 Animal Waste for Biofuels Production in Edo State

Animal waste in Edo State holds significant potential for biofuels production, with cattle manure alone contributing around 600,000 tons annually, which can produce up to 10,000 cubic meters of biogas. Poultry waste, amounting to approximately 150,000 tons per year, is suitable for biogas production, while pig manure, with an annual output of 100,000 tons, can also be used for biogas and composting. Additionally, goat and sheep manure, estimated at 50,000 tons annually, provides a further source for biogas production and organic fertilizer. Animal fats, especially from pigs and cattle, can be converted into biodiesel, with an estimated output of up to 5,000 liters per year. Despite the high potential, challenges such as inefficient collection, transportation, and processing infrastructure remain. To address these, solutions like developing centralized biogas plants near livestock farms, establishing proper waste collection and storage systems, and promoting small-scale biogas plants and biodiesel production facilities are crucial. Proper management of animal waste not only provides renewable energy but also helps in waste reduction and improved agricultural practices in the region.

Table 2. Energy Crops Commonly Cultivated in Edo State

Energy Crop	Description	Agro-Ecological Zone	Uses	Economic Significance
Oil Palm	Perennial crops yielding palm oil and kernel oil. Grows well in humid conditions.	Rainforest Zone	- Biofuel production (biodiesel) - Edible oil - Industrial applications	- Major cash crop - Supports biofuel industry and export
Cassava	Root crop with high starch content. Thrives in diverse conditions.	Rainforest and Derived Savanna Zones	- Ethanol production - Livestock feed - Food products	- Staple food crop - Source of income for smallholder farmers
Sugarcane	Tall perennial grass rich in sugar. Prefers waterlogged soils.	Freshwater Swamp Zone	- Bioethanol production - Sugar production	- Potential for renewable energy projects - Industrial sugar and ethanol production
Maize	Versatile cereal crop. Grows well in moderate rainfall areas.	Derived Savanna and Rainforest Zones	- Bioethanol production - Livestock feed - Food products	- Key to food security - Input for biofuel and livestock industries
Jatropha	Drought-resistant shrub with seeds rich in oil.	Derived Savanna Zone	- Biodiesel production - Medicinal uses	- Potential to enhance rural economy - Sustainable biofuel source
Plantain/Banana	High-yielding fruit crops suited to humid conditions.	Rainforest Zone	- Bioethanol production - Food products	- Food security crop - Adds value in biofuel production
Rice	Staple grain crop requiring waterlogged conditions.	Freshwater Swamp Zone	- Bioethanol production - Food products	- Supports rural livelihoods - Input for renewable energy projects
Groundnut (Peanut)	Legume rich in oil content. Grows in moderately dry conditions.	Derived Savanna Zone	- Biofuel production - Edible oil and protein-rich cake	- Significant for local industries - Enhances soil fertility through nitrogen fixation
Soybean	Legume rich in oil and protein. Prefers well-drained soils.	Derived Savanna Zone	- Biodiesel production - Protein supplements - Livestock feed	- Source of biodiesel and agricultural feedstock

Table 3. The Biofuel Production Potential in Edo State, Nigeria

Energy Crop	Biofuel Type	Estimated Production Potential (Tons/Year) *	Agro-Ecological Zone	Key Benefits	Challenges
Oil Palm	Biodiesel	300,000–500,000	Rainforest Zone	- High oil yield - Supports biodiesel production and by-products like glycerin	- Land-use conflict - Processing inefficiencies
Cassava	Bioethanol	200,000–350,000	Rainforest and Derived Savanna Zones	- High starch content - Widely grown and adaptable	- Competition with food security - High water requirement
Sugarcane	Bioethanol	150,000–250,000	Freshwater Swamp Zone	- High sugar yield for ethanol - Suited for swampy areas	- High water and labor requirement - Limited cultivation areas
Maize	Bioethanol	100,000–150,000	Derived Savanna and Rainforest Zones	- Multipurpose crop for food and fuel	- Susceptibility to pests - Competition with food security
Jatropha	Biodiesel	50,000–100,000	Derived Savanna Zone	- Non-food crop - Tolerates marginal lands	- Low awareness and adoption - High initial cultivation costs
Plantain/Banana	Bioethanol	50,000–80,000	Rainforest Zone	- High sugar and starch content for ethanol production	- Post-harvest losses - Low processing infrastructure
Rice	Bioethanol (Husk)	20,000–30,000	Freshwater Swamp Zone	- Utilizes agricultural waste (husks)	- Limited processing facilities - Competition with food production
Groundnut (Peanut)	Biodiesel	30,000–50,000	Derived Savanna Zone	- High oil yield - Suited for biodiesel production	- Susceptibility to drought and pests - Limited mechanization
Soybean	Biodiesel	40,000–60,000	Derived Savanna Zone	- High oil and protein content	- Competition with animal feed industry - Limited cultivation areas

Table 4. Estimated Agricultural Crop Residues for Major Crops Grown in Edo State:

Crop	Residue Type	Residue-to-Product Ratio (RPR)	Estimated Residue Production (Tons/Year) *	Uses	Challenges
Oil Palm	Fronds, kernel shells, fibers	3:1	600,000–900,000	- Biomass energy - Mulching - Briquette production	- High transportation cost - Low awareness of residue utilization
Cassava	Stalks, peels	0.3:1	60,000–100,000	- Animal feed - Biogas production - Organic fertilizer	- High perishability - Limited processing infrastructure
Sugarcane	Bagasse, tops, leaves	0.3:1	45,000–75,000	- Cogeneration (electricity) - Biogas production - Mulching	- Seasonal availability - Low residue recovery rate
Maize	Cobs, stalks, husks	1.5:1	150,000–225,000	- Biomass energy - Livestock feed - Composting	- Susceptibility to pests - Inadequate collection systems
Rice	Husks, straw	1.5:1	30,000–50,000	- Biomass energy - Briquette production - Animal bedding	- Dust pollution during processing - Limited recycling facilities
Groundnut (Peanut)	Shells, haulms	1:1	30,000–50,000	- Biomass energy - Animal feed - Organic mulch	- Low mechanization of shelling - Limited large-scale utilization
Plantain/Banana	Leaves, stems, peels	2:1	100,000–150,000	- Biogas production - Mulching - Fiber production	- High moisture content - Post-harvest losses
Soybean	Stalks, husks	1.5:1	60,000–90,000	- Biomass energy - Livestock feed - Soil enrichment	- Residue competition with other agricultural uses
Yam	Peels, vines	0.2:1	20,000–40,000	- Biogas production - Animal feed - Composting	- High moisture content - Limited large-scale recovery

Table 5. Waste Residues Generated in Edo State

Resource	Availability	Primary Uses	Potential for Biofuels
Oil Palm Residues	Abundant (20,000–25,000 tons annually)	Bioethanol, biodiesel production	Feedstock for biofuels
Sawdust and Wood Residues	Moderate (15,000–18,000 tons annually)	Heat generation, briquettes	Bioethanol, biogas
Cassava Peels	High (12,000–15,000 tons annually)	Animal feed	Bioethanol, biogas
Rice Husk	Moderate (10,000–12,000 tons annually)	Fertilizer, energy generation	Biogas
Municipal Solid Waste	Significant (200–300 tons/day in Benin City)	Waste-to-energy	Biogas, syngas

Table 6. Inventory of Aquatic Weeds for Biofuels Production in Edo State

Aquatic Weed	Scientific Name	Location	Biomass Potential	Biofuel Application	Challenges
Water Hyacinth	*Eichhornia crassipes*	Benin River Basin, wetlands	High lignocellulosic content	Bioethanol, biogas	High moisture content, harvesting logistics
Duckweed	*Lemna spp.*	Shallow water bodies, irrigation ponds	Rapid growth, nutrient absorption	Biogas, biodiesel	Small biomass yield, scalability
Cattails	*Typha spp.*	Wetlands, marshy areas	High cellulose and hemicellulose content	Bioethanol, briquettes	Difficult harvesting, processing requirements
Algae	Various species	Coastal regions, stagnant waters	High lipid content	Biodiesel, bioethanol	Algal bloom management, drying
Reeds	*Phragmites spp.*	Freshwater wetlands, riversides	High lignin and cellulose content	Bioethanol, biochar	Harvesting complexity
Salvinia	*Salvinia molesta*	Slow-moving rivers, ponds	Moderate biomass availability	Biogas, composting	Overgrowth in localized areas

Table 7. Animal Waste for Biofuels Production in Edo State

Animal Waste Type	Annual Biomass Potential	Biofuel Applications	Estimated Energy Production	Challenges
Cattle Manure	600,000 tons	Biogas, composting	Up to 10,000 cubic meters of biogas annually	Collection and transportation difficulties
Poultry Waste	150,000 tons	Biogas, composting	Biogas production for local energy needs	Storage and handling issues
Pig Manure	100,000 tons	Biogas, composting	Biogas production for cooking and heating	Inconsistent waste generation
Goat and Sheep Manure	50,000 tons	Biogas, composting	Biogas and organic fertilizer	Limited infrastructure for processing
Animal Fats (from pigs and cattle)	Varies by slaughter rate	Biodiesel production	Biodiesel production up to 5,000 liters per year	Processing requirements for biodiesel conversion

5. DISCUSSION

5.1 Agro-Ecological Zones of Edo State

The agro-ecological zones of Edo State significantly influence the region's agricultural productivity, ecological sustainability, and economic potential. The diversity across these zones provides distinct opportunities for crop cultivation, livestock farming, and renewable energy development, particularly in biomass production. The rainforest zone, characterized by high rainfall and fertile soil, supports the cultivation of perennial crops such as oil palms, cocoa, cassava, and plantain. This zone holds considerable potential for agro-industrial development due to its abundant resources. Studies, such as those by Abogunrin-Olafisoye et al. (2024), highlight the critical role of oil palm cultivation in food production and biofuel development, particularly biodiesel. However, challenges such as deforestation and soil erosion necessitate the adoption of sustainable land management practices to preserve this zone's productivity. The findings align with research by Ahmed and Olaitan (2024), which highlights the potential of forest zones in Niger state Nigeria for high-value cash crop production. However, the vulnerability of this zone to deforestation and soil erosion requires sustainable land management practices.

The derived savanna zone serves as a transition between the rainforest and drier savanna regions. Its balance of rainfall and dry periods makes it ideal for cultivating crops like maize, soybean, groundnut, and sorghum. This zone aligns with the state's efforts to enhance food security and bioethanol production. Ben-Iwo et al. (2016) emphasizes the zone's suitability for maize and cassava, which are critical feedstocks for ethanol production. However, the seasonal dryness in this zone may limit year-round productivity, highlighting the need for effective irrigation systems to sustain agricultural output. The results corroborate studies by Franke et al. (2018), which emphasize the adaptability of cereal and legume crops in derived savanna areas. However, this zone faces challenges such as seasonal droughts, necessitating the adoption of climate-resilient farming techniques.

The freshwater swamp zone, characterized by low-lying and waterlogged areas, is particularly suitable for crops like rice, sugarcane, and vegetables, making it a hub for flood-tolerant crop production. The zone's proximity to rivers facilitates irrigation but also poses risks such as flooding and salinization. Integrated water management strategies are essential for optimizing agricultural output in this zone while mitigating environmental risks. Studies by Okonkwo et al. (2021) confirm the potential of freshwater swamps in enhancing Nigeria's rice production capacity. Nonetheless, flooding and soil acidity are major concerns that require integrated water management systems.

The floodplain zone, enriched with nutrient-dense alluvial soils, supports the cultivation of rice, maize, and vegetables. These areas are crucial for intensive farming due to their natural fertility and access to water resources. However, seasonal flooding presents both opportunities and challenges. While flooding replenishes soil nutrients, it requires careful planning to harness agricultural potential and minimize environmental damage. These findings resonate with Ndubueze-Ogaraku et al. (2022), which highlight the importance of floodplain agriculture in increasing food security. However, sustainable flood control measures are critical to prevent crop damage and soil nutrient loss.

Compared to other Nigerian states, Edo's agro-ecological diversity offers a broader range of opportunities for food and energy crop cultivation. While states like Niger and Kwara excel in specific agro-ecological zones, Edo's combination of rainforest, savanna, and swamp zones enables a wider array of agricultural activities and renewable energy projects. The agro-ecological zones of Edo State provide opportunities for crop diversification, food security, and biofuel production. The Rainforest Zone supports perennial energy crops like Jatropha and oil palm, while the Derived Savanna and Freshwater Swamp Zones are favorable for cassava and sugarcane, key feedstocks for bioethanol. The agro-ecological zones of Edo State present immense opportunities for agricultural growth and renewable energy development. However, realizing this potential requires a strategic approach that integrates environmental sustainability, technological advancement, and robust policy frameworks. By addressing the unique challenges and leveraging the strengths of each zone, Edo State can achieve ecological and economic stability while contributing significantly to Nigeria's agricultural and energy sectors.

5.2 Biomass Inventory-Dependent Biofuel Generation

Biofuels, typically classified as liquid or gaseous fuels, are primarily derived from biomass. As a key component of the renewable energy sector, bioenergy focuses on producing energy from biomass in a way that maintains sustainability. Biomass-based biofuels are gaining increasing attention due to their potential to reduce reliance on fossil fuels, combat climate change, and enhance energy security. These biofuels include biohydrogen, biogas, biodiesel, and bioethanol, each representing a different stage in biofuel technology development.

First-generation biofuels (1st G) are primarily produced from food crops such as corn, sugarcane, sugar beet, wheat, rapeseed, soybean oil, sunflower, and palm oil. These crops are well-established as biofuel feedstocks, with mature technologies enabling efficient conversion into biofuels. 1st G biofuels are known for reducing atmospheric CO_2 emissions when they replace fossil fuels (Rodionova, et al., 2017). However, their reliance on food crops raises concerns about food security and land use competition, necessitating the exploration of alternative, more sustainable feed stocks.

Second-generation biofuels (2nd G) are derived from non-food biomass, such as agricultural residues, industrial waste, municipal solid waste, sewage sludge, and used cooking oils. These materials, often composed of lignocellulosic biomass (LCBs), are abundant and cost-effective, offering significant potential for large-scale biofuel production. The use of LCBs reduces fuel production costs and minimizes carbon footprints, as these feedstocks have little impact on food production or land use (Yadav, et al., 2020; Ben Hassen Trabelsi, et al., 2018). Biofuels from this generation include biodiesel, bioethanol, biomethanol, biobutanol, biogas, and biohydrogen, typically sourced from agricultural and forestry waste (Chandra, et al., 2012; Jeihanipour and Bashiri, 2015). Technological advancements in 2nd G biofuels have improved the efficiency of converting lignocellulosic biomass into fermentable sugars and other biofuels.

Third-generation biofuels (3rd G) represent a shift towards using microbial feedstocks like algae, bacteria, fungi, and yeast. Algae, in particular, have garnered attention for their high lipid content and rapid growth rate, making them an ideal source for biofuels. Unlike 1st and 2nd G biofuels, algae-based biofuels do not compete with food production and do not require arable land (Kumari and Singh, 2018). Additionally, microorganisms like bacteria, fungi, and yeast can produce biofuels such as bioethanol, biodiesel, and biobutanol from various waste products (Yadav, et al., 2020; Ben Hassen Trabelsi, et al., 2018). Ongoing research is focused on optimizing these biofuel production processes to create more sustainable and circular bioeconomies.

Fourth-generation biofuels (4th G) represent the forefront of biofuel technology, mainly derived from genetically modified organisms (GMOs) such as engineered microalgae, fungi, yeast, and cyanobacteria. This generation leverages advanced biotechnologies like genetic engineering and synthetic biology to improve biofuel production efficiency. 4th G biofuels often involve photobiological solar and electro-fuels, which use biological processes to directly convert solar energy into fuel. This approach, which relies on low-cost, abundant raw materials, has the potential to revolutionize energy storage and sustainability, making 4th G biofuels a leading candidate for addressing future global energy needs (Aro, 2016). Although still in its early stages, this field promises to offer innovative solutions to energy production and environmental challenges.

The progression from 1st G to 4th G biofuels reflects the growing sophistication and sustainability of bioenergy technologies. While 1st G biofuels have made significant strides in reducing fossil fuel dependence, concerns about food security and land use competition highlight the need to move toward 2nd, 3rd, and 4th G biofuels. These generations represent a more sustainable and circular bioeconomy, where waste and non-food biomass serve as valuable resources for biofuel production. Continued research and development hold great promise for the future of bioenergy, with emerging technologies set to deliver more efficient and environmentally friendly biofuels to meet global energy demands while mitigating climate change.

5.3 Agricultural Waste Resources in Edo State

Agro-waste represents an abundant and renewable source of biomass, originating from a variety of sources such as food processing, domestic activities, commercial kitchens, restaurants, and markets (Sarkar et al., 2017). Edo State is endowed with a vast array of agricultural resources, offering significant potential for bioenergy production. Biomass feedstocks, critical for bioenergy, can be classified into agricultural residues, forestry resources, urban waste, and other materials. The state's agricultural sector is pivotal in generating these feedstocks, positioning Edo State as a key contributor to Nigeria's bioenergy development efforts.

Agriculture in Edo State is predominantly based on traditional smallholder farming systems. Small-scale farmers utilize simple techniques such as bush-fallow cultivation, a practice common in Nigeria (FAO, 2005; Aregheore, 2005). Despite these rudimentary methods, agriculture remains a cornerstone of the economy, contributing two-thirds of Nigeria's total agricultural output (Aregheore, 2005). Historically, agriculture was the backbone of Nigeria's economy before the discovery of oil and continues to play a vital role in GDP and export revenue generation (Aregheore, 2005).

Edo State's humid tropical climate, with an annual rainfall exceeding 2,000 mm in certain regions, supports the cultivation of a wide range of crops. Staples such as cassava, rice, and yams thrive in the region, alongside cash crops like cocoa, oil palm, and rubber, which are prominent in the southern humid zones of Nigeria (FAO, 2005; Aregheore, 2005). The favorable agro-ecological conditions enable the state to maintain its agricultural productivity, contributing significantly to both local and national economies.

Agricultural waste (AW), as defined by the United Nations (1997), encompasses waste generated from farming operations, including manure, harvest residues, fertilizer runoff, and pesticide contamination. These waste streams intersect across modern agricultural practices, spanning crop waste, animal waste, processing waste, and hazardous waste such as pesticides (Nagendran, 2011).

Edo State's rich agricultural landscape offers substantial opportunities for harnessing agricultural waste for bioenergy production. By converting these waste streams into energy, the state can address waste management challenges, reduce greenhouse gas emissions, and contribute to Nigeria's sustainable development goals. Developing efficient waste-to-energy systems in Edo State could serve as a model for other regions, highlighting the potential of agricultural waste as a cornerstone of Nigeria's renewable energy future.

5.4 Biomass Feedstocks and Energy Crops

Edo State's agricultural resources present significant potential as biomass feedstocks for bioenergy production, with energy crops such as sugarcane, cassava, sweet sorghum, and maize standing out due to their high energy content and adaptability to the region's environmental conditions. These crops are particularly valuable because they can be cultivated on both prime and marginal or degraded lands, which helps optimize land use and ensures the effective utilization of available agricultural space. Additionally, Edo State's humid tropical climate, combined with consistent rainfall patterns, makes it an ideal environment for the cultivation of these energy crops, further enhancing their suitability for biofuel production (Edenhofer et al., 2011; Huber et al., 2006).

Nigeria, including Edo State, is endowed with vast arable land and abundant water resources, both of which are essential for supporting the large-scale cultivation of energy crops and the production of biofuels (Abila, 2010; GOPA, 2015). The state's natural resources create a favorable foundation for growing energy crops, contributing to the potential for sustainable bioenergy solutions.

Among the various energy crops, cassava and sugarcane are particularly notable as key feedstocks for biofuel projects in Nigeria, including those in Edo State. Cassava, a versatile and widely cultivated crop, is primarily used in the production of bioethanol, offering high starch content that can be efficiently converted into renewable energy. In contrast, sugarcane not only serves as a significant source of bioethanol but also provides bagasse, a fibrous residue that can be utilized for electricity generation. Both crops have shown substantial promise in Nigeria's biofuel sector, with growing areas of land being dedicated to their cultivation as part of the country's renewable energy strategy (Abila, 2010; GOPA, 2015). These crops play an integral role in the development of a sustainable biofuel industry in Edo State, supporting both energy production and economic growth in the region.

Also, aquatic weeds in Edo State present a promising opportunity for the development of biofuels, as these plants, often viewed as environmental nuisances, possess high biomass yields and are rich in cellulose, lignin, and sometimes oils, which make them viable feedstocks for bioenergy production. Aquatic weeds such as *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), *Salvinia molesta* (giant salvinia), and *Hydrilla verticillata* (hydrilla) are prevalent in many water bodies in Edo State, which are part of the state's extensive river and wetland systems. These species, though typically viewed as invasive, have shown significant potential for use in biofuels, especially as alternative sources of renewable energy.

Recent studies have emphasized the bioenergy potential of aquatic weeds due to their rapid growth and high biomass accumulation. According to Chen et al. (2022), aquatic weeds are among the most prolific biomass producers, and their fast growth cycles and high moisture content make them ideal candidates for biofuel production. The high cellulose content found in these plants is particularly significant because cellulose can be converted into fermentable sugars for bioethanol production. Research by Ezzariai et al. (2021) demonstrated that water hyacinth, one of the most common aquatic weeds, can be effectively utilized for bioethanol production through enzymatic hydrolysis and fermentation processes.

In addition to bioethanol, aquatic weeds are also promising candidates for biogas production. Aquatic plants, especially *Eichhornia crassipes* and *Salvinia molesta*, have been shown to yield high amounts of methane when subjected to anaerobic digestion. This process, as explored by Moretti et al. (2022), produces biogas that can be used for electricity generation, presenting an efficient way to convert aquatic biomass into renewable energy. According to a study by He et al. (2022), the potential of aquatic weeds like water hyacinth in biogas production is further enhanced by their high nitrogen and phosphorus content, which supports microbial activity during anaerobic digestion, leading to higher methane yields.

Furthermore, the oils present in certain aquatic weeds, including *Pistia stratiotes*, have been identified as valuable sources for biodiesel production. Research by Nawaj Alam et al. (2021) found that the oil content in *Pistia stratiotes* can be extracted and converted into biodiesel through transesterification processes. This finding is particularly important for expanding the scope of biofuels in Edo State, where the presence of such weeds can be harnessed to produce biodiesel as an alternative to traditional fossil fuels.

Edo State's favorable climatic conditions, which include abundant rainfall and fertile soil, support the growth of these aquatic weeds. The region's extensive river systems and wetlands are ideal for the proliferation of aquatic plants, which often thrive in nutrient-rich waters, making them both an environmental concern and an untapped resource for bioenergy. Studies by Kaur et al. (2018) have suggested that proper management of aquatic weed biomass, through harvesting and processing into biofuels, could alleviate some of the negative environmental impacts associated with their growth, such as water eutrophication, reduced biodiversity, and disrupted water transport.

Additionally, the harvesting and processing of aquatic weeds for biofuel production offer economic opportunities. The collection, processing, and conversion of these weeds into biofuels can create local employment opportunities and provide income for rural communities involved in the harvesting and conversion process. According to Kaur et al. (2018), the integration of biofuel production from aquatic weeds into local economies could promote sustainable livelihoods and contribute to rural development while addressing the challenges of invasive aquatic weed management.

A comprehensive inventory of aquatic weeds in Edo State is crucial to assess their distribution, biomass potential, and growth patterns. Such an inventory would provide valuable data on the most suitable species for biofuel production and inform strategies for their sustainable management. According to research by Jekayinfa et al. (2020), detailed mapping of aquatic weed species and biomass availability is critical to determine the economic feasibility and environmental impact of large-scale biofuel production projects.

In conclusion, the inventory and potential utilization of aquatic weeds for biofuel production in Edo State presents a unique and promising opportunity for sustainable energy development. By harnessing these abundant yet underutilized aquatic plants, Edo State could contribute significantly to Nigeria's bioenergy sector while addressing environmental challenges, creating jobs, and promoting rural economic development.

6. CONCLUSION

The biomass resource assessment using the inventory approach for biofuel production potential in Edo State has highlighted the significant role of the region's diverse agricultural and aquatic biomass resources in supporting the development of sustainable bioenergy solutions. Through the systematic inventory of various biomass feedstocks, including agricultural residues, energy crops, and aquatic weeds, this study has provided valuable insights into the availability, distribution, and biofuel production potential of these resources.

The assessment has demonstrated that Edo State possesses an abundant supply of biomass, ranging from crop residues such as cassava, sugarcane, and maize, to aquatic plants like water hyacinth and water lettuce, which are often considered invasive but offer high biomass yields suitable for biofuel production. The climate and environmental conditions of Edo State, characterized by favorable rainfall patterns and fertile soil, further enhance the viability of these resources for large-scale bioenergy projects.

By employing an inventory approach, this study has not only mapped the biomass resources but also identified key areas where biofuel production can be maximized, particularly through the cultivation of energy crops and the harvesting of aquatic weeds. These findings suggest that Edo State has the potential to become a significant player in Nigeria's bioenergy sector, contributing to the nation's energy security, reducing greenhouse gas emissions, and promoting sustainable development.

Moreover, the integration of these biomass resources into biofuel production aligns with global sustainability goals, including the transition to renewable energy, waste reduction, and the mitigation of environmental impacts associated with fossil fuel use. The development of biofuel projects based on these resources will also provide economic opportunities, particularly for rural communities, through job creation in biomass harvesting, processing, and bioenergy production.

The results of this biomass resource assessment emphasize the need for further research, policy support, and infrastructure development to fully realize the biofuel potential of Edo State's biomass resources. By leveraging these abundant resources in a sustainable and efficient manner, Edo State can contribute to Nigeria's efforts to diversify its energy portfolio, improve environmental quality, and foster economic growth. Ultimately, the successful implementation of biofuel production projects will enhance Edo State's role as a leader in renewable energy within Nigeria and the broader West African region.

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Conflicts of Interest
The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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