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LIFE CYCLE ASSESSMENT OF BIOENERGY SYSTEMS VERSUS FOSSIL FUEL ALTERNATIVES: INSIGHTS FOR SUSTAINABLE ENERGY TRANSITIONS IN NIGERIA

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Background: The pressing necessity to address climate change has positioned energy decarbonization at the forefront of global sustainability initiatives. Decarbonization entails diminishing carbon intensity throughout the energy value chain by transitioning from fossil fuels to low- or zero-carbon alternatives, including renewable energy, green hydrogen, and bioenergy. Nigeria, despite its abundant fossil fuel resources, experiences persistent energy instability marked by inconsistent electricity delivery, low access rates, and excessive reliance on petroleum goods. The incorporation of renewable energy sources, including solar, wind, biomass, and small hydropower, has become an essential strategy for attaining energy security, sustainability, and climate resilience. Investing in renewable energy diminishes reliance on fossil fuels while fostering job development, energy fairness, and environmental conservation. **Objectives:** The main objective of the current study is to comparison of environmental impacts through life cycle assessment (LCA) of two energy systems in Nigeria, namely bioenergy systems using locally available biomass as agricultural waste and traditional fossil fuel-based systems. It is expected that the study will identify key features of the two energy production approaches and provide a scientifically sound basis for the selection of cleaner energy sources, thereby facilitating Nigeria's transition to a low-carbon economy. **Methods:** The following databases were used in searching for secondary data used for this study: Scopus, Web of Science, ScienceDirect, Google Scholar, African Journals Online (AJOL). The keywords used for this search were: "Lifecycle Assessment", "LCA", "bioenergy", "biomass", "fossil fuels", "Nigeria", "sustainable energy", "greenhouse gas emissions", "renewable energy Nigeria". The inclusion criteria were considered in the course of this review: Studies focused on Nigeria or similar Sub-Saharan African contexts, Peer-reviewed articles, LCA studies, government and NGO reports, Publications in English from 2000 to 2024. The following exclusion criteria were used for this review: Non-peer-reviewed blogs, editorials, and news articles, Studies lacking clear LCA methodology. **Results:** The findings underscore the critical role of lifecycle thinking in guiding energy policy and project implementation in developing countries facing the dual challenge of expanding energy access and combating climate change. **Conclusion:** The lifecycle assessment of bioenergy systems compared to fossil fuel alternatives provides critical insights for shaping sustainable energy transitions in Nigeria. While fossil fuels have historically powered the nation's economy, their environmental and health impacts underscore the urgent need for cleaner alternatives. Bioenergy, with its potential to reduce greenhouse gas emissions, promote rural development, and utilize locally available biomass resources, presents a promising pathway toward sustainability.

Keywords: life cycle assessment; decarbonization; bioenergy; sustainability; biomass; agricultural waste; fossil fuels; energy transition; environmental impact; greenhouse gases.

INTRODUCTION

Nigeria's pursuit of a sustainable and resilient energy future has rendered the environmental consequences of energy production a paramount priority. Life Cycle Assessment (LCA) offers a thorough framework for assessing the environmental performance of energy systems from resource extraction to production, utilization, and disposal. Bioenergy systems, especially those utilizing locally sourced biomass like agricultural leftovers, are increasingly advocated as cleaner substitutes for fossil fuels. In contrast to fossil energy sources, which contribute significantly to greenhouse gas emissions, air pollution, and environmental degradation, bioenergy systems possess the capacity to diminish carbon footprints, bolster energy security, and foster rural economic development (Ishola et al., 2020).

The sustainability of bioenergy is not certain and is significantly influenced by the type of feedstock, conversion technology, and local implementation methods. From a comprehensive lifecycle viewpoint, many bioenergy methods may still present environmental challenges, including land use alteration, water utilization, or emissions during processing and transportation. Consequently, it is imperative to compare the life cycle implications of bioenergy with those of fossil fuels to guide policy decisions in Nigeria's developing energy sector (Adepoju et al., 2022). This paper examines these contrasts and provides recommendations on how Nigeria might utilize LCA findings to enhance its sustainable energy transition.

Background on global energy decarbonization

The pressing necessity to address climate change has positioned energy decarbonization at the forefront of global sustainability

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initiatives. The energy sector, accounting for more than 70% of global greenhouse gas emissions, is a primary target of climate mitigation initiatives (IEA, 2021). Decarbonization entails diminishing carbon intensity throughout the energy value chain by transitioning from fossil fuels to low- or zero-carbon alternatives, including renewable energy, green hydrogen, and bioenergy (Rogelj et al., 2018). International frameworks like the Paris Agreement have expedited initiatives for achieving net-zero emissions, compelling nations to embrace cleaner technology and reduce reliance on coal and oil (UNFCCC, 2015; Chishti et al., 2024; Xia et al., 2024). Progress in solar, wind, and bioenergy technologies, along with energy efficiency initiatives and the electrification of transportation and industry, has rendered profound decarbonization progressively attainable (Rockström et al., 2017). Nonetheless, inequalities in technical availability, funding, and policy execution persist as significant obstacles, especially in poor nations. Thus, attaining global energy transition objectives necessitates synchronized policy backing, technical advancement, and investment in cleaner energy infrastructures (IRENA, 2020).

Nigeria's energy insecurity and the need for renewables

Nigeria, despite its abundant fossil fuel resources, experiences persistent energy instability marked by inconsistent electricity delivery, low access rates, and excessive reliance on petroleum goods. In 2023, about 85 million Nigerians, approximately 40% of the population, are without power access, especially in rural regions (World Bank, 2023). The national grid experiences recurrent outages, inadequate investment, and inefficiency, resulting in a significant reliance on diesel and petrol generators, which are both expensive and environmentally harmful (Oyedepo, 2012).

The situation is further worse by escalating fuel prices, deteriorating infrastructure, and an increasing population, all of which burden current energy systems. The incorporation of renewable energy sources, including solar, wind, biomass, and small hydropower, has become an essential strategy for attaining energy security, sustainability, and climate resilience (Raza & Shakeel, 2025). Renewable energy provides decentralized and scalable solutions that align with Nigeria's varied topography and rural populations (Nkalo, 2025). Furthermore, the shift to clean energy is consistent with Nigeria's obligations under the Paris Agreement and its Energy Transition Plan, which aims for net-zero emissions by 2060 (FGN, 2021). Currently, fossil fuels remain the predominant fuel source in Nigeria (Figure 1). Investing in renewable energy diminishes reliance on fossil fuels while fostering job development, energy fairness, and environmental conservation.

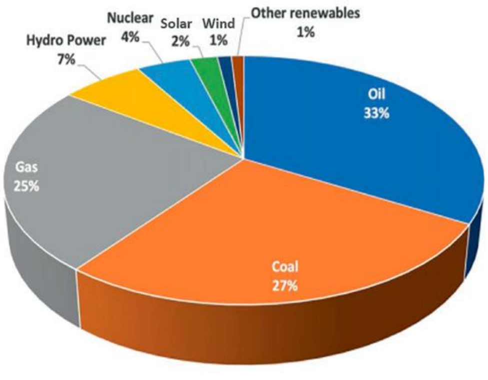

Figure 1. Nigeria's energy mix (2023): fossil vs. renewable contributions. Proportion of Nigeria's electricity generated from gas, oil, hydropower and biomass (Adeshina et al., 2024, *Creative Commons Attribution License International CC-BY 4.0*)

The main objective of the current study is to comparison of environmental impacts through LCA of two energy systems in Nigeria, namely bioenergy systems using locally available biomass as agricultural waste and traditional fossil fuel-based systems. The study seeks to assess and measure greenhouse gas emissions, energy efficiency, resource sustainability and overall environmental impacts for each energy pathway from production to consumption. It is expected that the study will identify key features of the two energy production approaches and provide a scientifically sound basis for the selection of cleaner energy sources, thereby facilitating Nigeria's transition to a low-carbon economy.

It is expected that a comparative life cycle analysis of two alternative energy systems based on ISO 14044 will identify potential limitations, problem areas in the use of bioenergy using local biomass in Nigeria, and most importantly, will demonstrate the regional diversity of biomass in Nigeria and its energy potential for the transition to green energy and a circular economy.

LITERATURE REVIEW

Life cycle assessment (LCA) and its significance

LCA is a defined process employed to assess the environmental implications of a product or system across its entire life cycle, from raw material extraction to disposal (Kaufman, 2013). In energy systems, LCA has emerged as a crucial instrument for evaluating sustainability and informing policy decisions, especially in the comparison of renewable and non-renewable energy sources (Cherubini et al., 2011). Although numerous global studies have utilized LCA for diverse bioenergy and fossil fuel systems, context-specific evaluations for nations such as Nigeria are scarce.

Bioenergy potential and LCA studies in Nigeria

Nigeria has considerable bioenergy potential derived from agricultural wastes, forest biomass, and municipal garbage (Akinbami et al., 2001). Feedstocks like cassava peels, oil palm leftovers, maize stalks have been recognized as viable options for second-generation biofuels (Emmanuel & Grace, 2022). Fibre and shells such as palm leftovers can be used as boiler fuel to produce carbon-based natural electricity and steam on-site through carbon sequestration during biomass growth (Archer et al., 2018). On the other hand, due to the high yield of oil palm among other oil crops, some countries are considering palm oil as a promising feedstock for biodiesel production (Pleanjai & Gheewala, 2009; Yee et al., 2009). Researchers in Nigeria are exploring the potential of anaerobic biodegradation of cassava peels, both fresh and on stale, to produce biogas due to the high potential of this waste identified in earlier studies (Aisien & Aisien, 2020; Igbum et al., 2019). Nonetheless, a significant deficiency exists in LCA studies evaluating the environmental consequences of utilizing these resources in the Nigerian setting. Most current research emphasizes technical feasibility or production optimization, neglecting comprehensive environmental impact assessments (Ahmethodzic & Music, 2021).

Fossil fuel systems and their environmental consequences

Nigeria's energy infrastructure predominantly depends on fossil fuels, especially diesel and natural gas, which substantially contribute to greenhouse gas emissions and air pollution (Khan et al., 2020). Life Cycle Assessment (LCA) studies in many nations continually demonstrate that fossil fuel systems possess greater carbon footprints and adverse environmental externalities in comparison to bioenergy alternatives (Dalir et al., 2018; Pires et al., 2024). Nevertheless, limited Nigerian assessments evaluate these implications throughout complete life cycles.

Comparative LCA: global and African perspectives

International LCA comparisons indicate that bioenergy is more sustainable than fossil fuels for greenhouse gas emissions, acidification, and fossil energy depletion (Nordin et al., 2024; Ma et al., 2025; Wang & Azam, 2024). Recent LCA study in Ghana and South Africa has underscored the potential of biomass-to-energy conversion in Sub-Saharan Africa to mitigate environmental consequences and enhance energy accessibility (Mukoro et al., 2021). These studies highlight the significance of localized LCA, since area agriculture practices, land utilization, and energy compositions can profoundly influence results.

Policy and research deficiencies in Nigeria

Notwithstanding governmental attempts such as Nigeria's Energy Transition Plan (2021), there exists a deficiency of empirical data and life cycle assessment-based information to inform decision-making over the deployment of renewable energy. Consequently, policymakers frequently depend on generalized models that may not accurately represent Nigeria's distinct socio-environmental and energy dynamics (Nordin et al., 2024). A Nigeria-specific LCA is essential to address this gap and inform context-sensitive energy strategy.

Summary of global studies on LCA of energy systems

Bioenergy versus fossil fuels

Global LCA studies regularly demonstrate that bioenergy systems exhibit markedly reduced greenhouse gas emissions throughout their lifecycle in comparison to fossil fuel systems. (Cherubini & Strømman, 2011) discovered that biofuels produced from residues and garbage can diminish life cycle greenhouse gas emissions by 60 – 90% in comparison to gasoline and diesel. This is especially applicable to second-generation biofuels that circumvent land use change and competition for food resources.

Renewable energy systems

Life cycle assessments of renewable energy sources, including solar, wind, and hydropower, indicate negligible emissions while operation; yet, they exhibit certain environmental implications during the manufacturing and end-of-life phases (Bruckner et al., 2026). Solar photovoltaic systems provide little greenhouse gas emissions (about 20 – 70 gCO_2-eq/kWh); yet, they require substantial energy and materials during panel manufacturing (Fthenakis & Kim, 2011).

Fossil fuel energy systems

Traditional fossil fuel systems, such as coal and oil, have elevated lifecycle emissions, predominantly during extraction, combustion, and waste disposal. Coal-fired power stations release more than 800 – 1000 gCO_2-eq/kWh, even with the incorporation of carbon capture systems (Pehnt, 2006).

Key findings on environmental and social trade-offs

Ecological trade-offs

Land Use Change: Bioenergy systems, particularly those utilizing specific crops, may result in deforestation and a decline in biodiversity as a consequence of land use conversion (Fabiosa et al., 2008). This is a significant issue in forest-dense regions such as Nigeria.

Water Utilization and Eutrophication: The generation of biofuels frequently necessitates substantial irrigation and can result in nutrient discharge, contributing to freshwater eutrophication and the deterioration of aquatic ecosystems (Bruckner et al., 2014).

Greenhouse Gas Emissions (GHG): Although bioenergy systems diminish lifecycle GHG emissions relative to fossil fuels, emissions resulting from fertilizer application, transportation, and land-use alterations may counteract some advantages if inadequately managed (Cherubini & Strømman, 2011). The combustion of biomass can emit particles and pollutants such as NO_x and SO_2, particularly in conventional or low-efficiency combustion systems (Pehnt, 2006).

Societal trade-offs

The Food vs Fuel Debate: The utilization of food-based biomass, such as corn and cassava, may impact food supply and pricing in low-income areas (Rosegrant et al., 2013).

Employment and Income Generation: The advancement of bioenergy, especially through small-scale and localized biomass systems, has the potential to provide rural employment and invigorate economic activity (Bruckner et al., 2026).

Decentralized bioenergy systems can improve energy availability and equity in off-grid rural communities. Nonetheless, variations in infrastructure and policy support may restrict the equal allocation of benefits (Cherubini & Strømman, 2011).

Ahmed et al. (2021) developed a framework for environmental and socio-economic interactions in the context of the energy transition (Figure 2). At the same time, a visual block diagram illustrating the interrelated environmental and socio-economic consequences of bioenergy is presented by Herzog et al. (2001) (Figure 3).

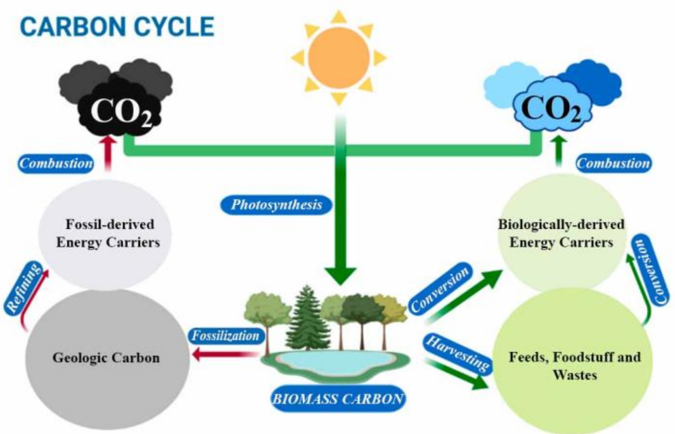

Figure 2. Conceptual framework: environmental and socioeconomic interactions in energy transitions (Ahmed et al., 2021, *Creative Commons Attribution License International CC-BY 4.0*)

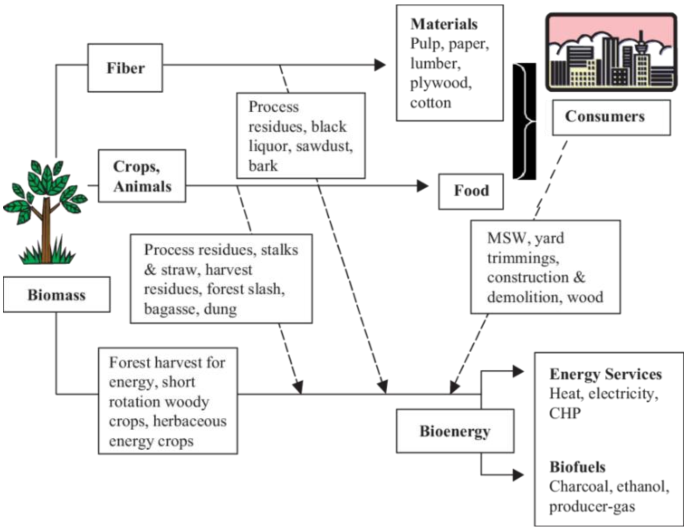

Figure 3. A flowchart illustrating interlinked environmental and socioeconomic impacts of bioenergy (Herzog et al., 2001, *Creative Commons Attribution License International CC-BY 4.0*)

Gaps in literature relevant to sub-Saharan Africa and Nigeria

Most LCA studies have been conducted in developed countries using datasets and assumptions that do not accurately reflect African infrastructure, biomass diversity, or socio-economic conditions (Bruckner et al., 2014). Empirical life cycle assessment data for local feedstocks such as cassava peel and oil palm residues are scarce. A literature review found that most biodiesel LCA studies only cover one critical environmental impact and focus on emissions of greenhouse gases and other hazardous compounds such as sulphur oxides and nitrogen oxides (Castanheira & Freire, 2017; Archer et al., 2018), but only about 4% of studies also assessed land use impacts and resource damage, which is important due to the significant impact of land use practices on soil quality (Chatterjee et al., 2015).

Omission of social aspects

Numerous African-centric studies prioritize energy and emissions, although infrequently incorporate social variables such as health consequences, job effects, gender equity, or land tenure considerations within LCA frameworks. Insufficiently Developed Policy-Relevant LCA Tools. Nigeria is deficient in standardized LCA databases and localized emissions variables, hindering policymakers' capacity to properly compare energy routes. Integrated LCA tools are required to fit with Nigeria's energy, agriculture, and climate change policies (Table 1).

METHODOLOGY

The comparative LCA of the two energy systems was used as the research method, as this approach is internationally recognized as a tool for determining the environmental impact of any process. The method used is based on the requirements of ISO 14040 and ISO 14044 standards and provides high transparency and reproducibility of the results obtained. The comparison of the environmental impacts of bioenergy and fossil fuel energy systems in the Nigerian context aims to provide an assessment using the cradle-to-grave approach. The system boundaries are defined by the following processes: biomass cultivation/raw material extraction, biofuel/traditional fuel production, transportation processes and end-use for energy, waste management.

Table 1. Summary of global LCA findings comparing bioenergy and fossil fuels

Source	Country	Feedstocks	GWP range, gCO_2-eq/MJ	Water use, L/MJ	Key findings
Cherubini & Strømman, 2011	Norway (Global)	Wood, agricultural residues	15 – 50	1 – 5	Bioenergy reduces GHGs vs. fossil fuels, but results vary by feedstock & region
Cherubini et al., 2011	China	Corn stover, algae	20 – 60	10 – 70	Algae has higher water use but low GHG emissions; land use minimized
Pehnt, 2006	Germany	Forest biomass	25 – 40	2 – 4	GHG emissions are lower than coal; transport logistics impact results
Ghiat & Al-Ansari, 2021	Nigeria/ South Africa	Cassava peel, maize husks	30 – 55	15 – 50	Bioethanol from residues is viable; data gaps hinder local-specific analysis
Searchinger et al., 2008	USA	Corn	60 – 90 (with land-use)	300 – 500	Indirect land-use change may make biofuels worse than gasoline in GWP
Bruckner et al., 2014	Global review (multi-country)	Various	10 – 100	Varies	Emphasizes variability in results; recommends regionalized LCA tools

The main objective of this study is to assess the environmental impact of bioenergy systems using bioethanol from local oil palm biomass compared to fossil fuel-based energy systems such as diesel in Nigeria. The rationale for choosing oil palm for biodiesel production in the current study is the availability of an established and robust process technology as well as highly productive feedstock cultivation and palm oil extraction technology, which holds great promise for future generations of biofuels, bioenergy and bioproducts (Archer et al., 2018). A comparative assessment of both approaches was conducted, assuming that 1 MJ of useful energy is obtained from the combustion of bioethanol or diesel. This allows for consistent and meaningful comparisons between different energy systems, regardless of their physical form (solid, liquid or gaseous), energy content or conversion efficiency. According to the standard, LCA consists of four steps: defining the goal and scope, inventory analysis, impact assessment, and interpreting the results of each of the three previous steps.

Each process step was quantified per MJ of useful energy, allowing normalized comparisons between bioenergy and fossil fuel systems based on published literature data.

To obtain the source data, a search was conducted for scientific publications containing experimental data related to bioethanol production from biomass and diesel, as well as ongoing research on LCA of bioethanol and diesel. In selecting the sources of information, preference was given to validated papers, original and review articles published in peer-reviewed journals or reputable scientific literature publishers. Statistical databases were analysed, in particular the Nigerian National Statistics, which provides data related to agriculture, energy consumption and environmental aspects specific to the country, ensuring local relevance and accuracy. Life cycle assessment databases such as ecoinvent and GREET were also searched. The data were summarized to allow visual comparison.

Goal and scope definition

The study aims to identify the differences in environmental performance and efficiency of the two energy systems.

The technical requirements of energy generation devices are different due to the difference in the combustion process of biomass fuel and traditional fuel. However, the applied equipment for generating two different types of energy can be considered similar in general (Guo et al., 2022). The main materials used in both systems are steel, copper, aluminium, glass, polyethylene, the transportation of raw materials and finished products is generally carried out by heavy-duty gas-powered vehicles, and the use stage for energy mainly involves the emission of greenhouse gases. Waste includes recyclable materials and non-recyclable materials. Recyclable materials are reused after recycling, and non-recyclable materials should be sent to landfill (Zhu & Bi, 2025).

The following assumptions were made in this step: the processes such as building construction and equipment manufacturing are considered background processes with little contribution, and therefore are not taken into account.

Inventory analysis

The purpose of the inventory is to assess the material and energy flows entering and leaving the system. The stages of the inventory are (Zhu & Bi, 2025):

– Biofuel production vs. traditional fuels: growing of feedstock (all life stages of oil palm such as land preparation, planting, fertilization, plant protection with pesticides and harvesting (Chatterjee et al., 2015)) vs. extraction of feedstock (assessment of deposits and environmental risks, preparation of infrastructure and technical preparation, well drilling, extraction, cleaning); processing of feedstock to obtain biofuels or traditional fuels. The processes involve land exploitation and depletion, consumption of water, energy and some substances (mainly chemicals) and emissions of pollutants (Waheed et al., 2023; Obi & Okongwu, 2016; Zhu & Bi, 2025; Rogowska & Wyrwa, 2021). Biodiesel production inventories have focused on the main steps, such as the agricultural stage, the stage of palm oil production from cultivated raw materials and transesterification; and on the preparatory stages, such as washing, cleaning, and drying with air blown at base pressure (Chatterjee et al., 2015). Palm oil production is carried out by chemical or mechanical extraction, which affects the amount of final product yield and the energy or substance costs. A reliable and technically feasible method for transesterification in Nigeria is mechanical extraction, which does not require additional chemicals and yields 70 – 80% oil using a motor-driven screw press and 60 – 65% using a hand press. This oil is then filtered through a filter press prior to the transesterification process (Chatterjee et al., 2015). Methyl ester (aka biodiesel) is produced in the transesterification process at up to 98% by reacting palm oil with methanol in the presence of a catalyst (usually NaOH) for 90 min at 60 °C, where glycerol is formed as a by-product. Alkaline transesterification is well documented in the literature and has been successfully applied to a variety of biomass feedstocks. In addition, the technology is highly scalable to industrial scale and offers favourable cost efficiencies compared to other methods, and most importantly, the technology is compatible with the infrastructure and technical expertise available in Nigeria. For this reason, this method of producing biodiesel was considered in the current study.

– Collection and transportation: covers the logistics process of products, namely raw biomass from agricultural sites or fossil fuels from the mining site, as well as intermediate products of production to processing plants; covers the accounting of water consumption, energy and carbon emissions (depending on the means of transport used) (Zhu & Bi, 2025).

– End-use, including combustion of biofuels and conventional fuels for electricity, heating or transport.

– End-of-use disposal (for residues/emissions): the energy costs of transporting waste to landfill, recycling recyclables, landfilling non-recyclable waste and disposing of process residues, wastewater and emissions throughout the service life (Rogowska & Wyrwa, 2021). Recovery rates, energy consumption for recycling and energy consumption for landfilling of different types of raw materials are presented in Jing et al. (2012), and the estimated energy consumption at the scrap recycling stage is presented in Zhu & Bi (2025).

The boundaries of the study are presented in Figure 4.

Impact assessment

The key impact categories were those that are most important for the sustainable development of Nigeria, namely: 6 environmental impact criteria were selected for each life cycle (per unit of 1 MJ of energy):
1) GHG emissions (in CO_2 equivalent);
2) energy consumption for production;
3) water consumption;
4) acid/toxic impact;
5) waste generation;
6) renewability.

The criteria were selected in such a way as to take into account the specifics of most areas of Nigeria, such as the need for sustainable and renewable energy, reduction of greenhouse gas emissions to reduce the risk of global climate change, freshwater costs as an important criterion for Nigeria experiencing water shortages, the potential for harmful effects of toxic chemicals to reduce the risk of population and child diseases (Shen et al., 2021). Impact assessment metrics are presented in Table 2.

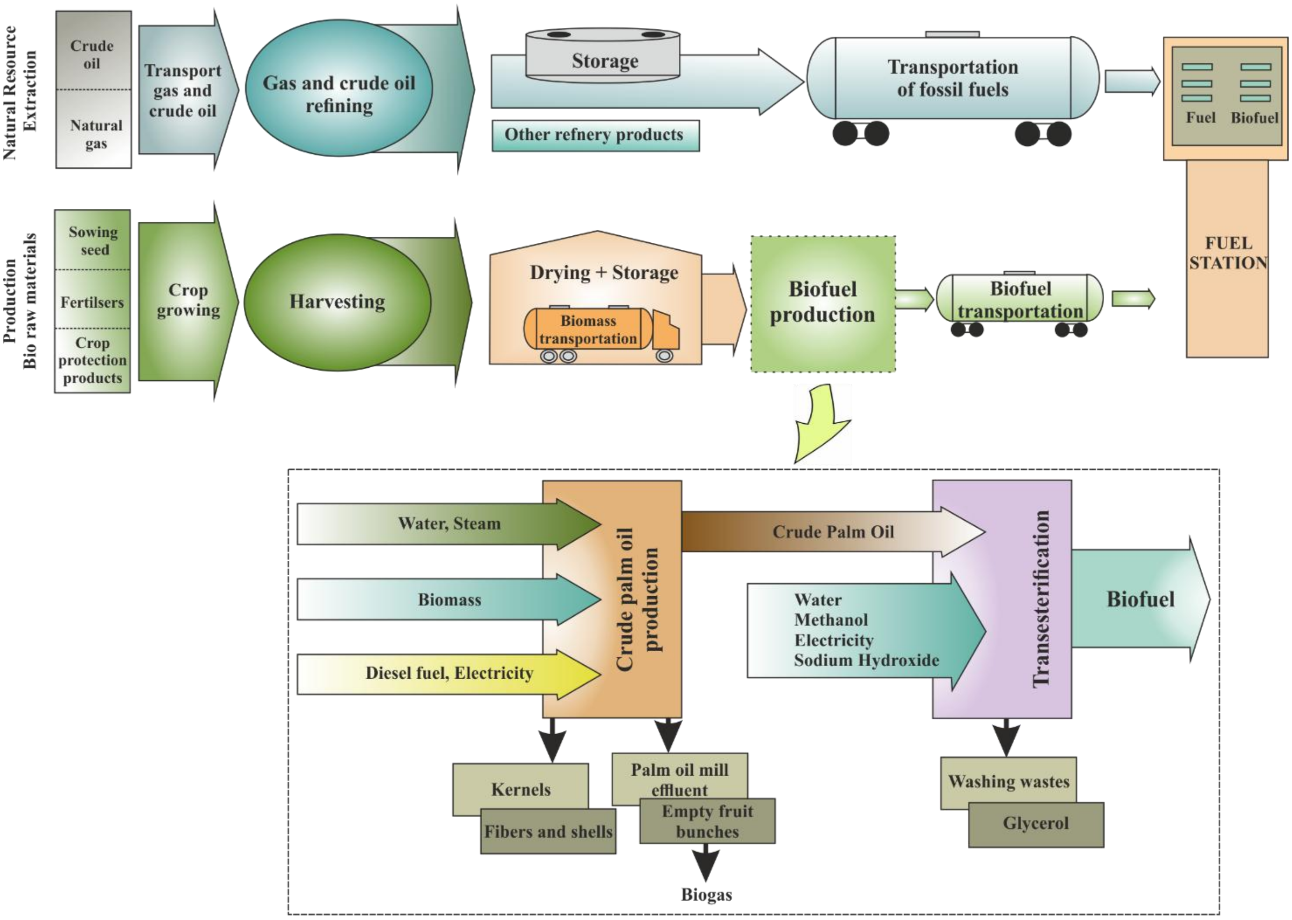

Figure 4. Life cycle process of two compared fuels
(Own development based on Pleanjai & Gheewala, 2009; Spirinckx & Ceuterick, 1996; Archer et al., 2018)

Table 2. Impact categories and metrics used in the study

Impact category	Measurement unit	Significance
Global Warming Potential (GWP)	g CO_2-equivalent (gCO_2-eq)	Quantifies greenhouse gas emissions contributing to climate change and global warming.
Water Consumption	cubic meters (m^3)	Assesses freshwater use, highlighting potential stress on local water resources.
Human Toxicity	Comparative Toxic Unit (CTU)	Evaluates the potential harm of toxic emissions on human health during the lifecycle stages.

Interpretation

The LCA interpretation included a completeness and consistency check, as well as a contribution analysis, in which aspects of the systems with the highest impact contribution were checked for rigor and correctness. For better clarity, a spider diagram (Radar chart) was constructed using RAWGraphs (online) (https://app.rawgraphs.io/). The data was prepared in Excel. Since such a diagram allows displaying several different categories, for convenience, all values were normalized, that is, brought to a scale from 0 to 1, where an environmentally safe state (i.e. the best result) is taken as 0, and an environmentally hazardous state, respectively, 1. Since the criterion "Renewability" can only be assessed as "yes, renewable" and "no, not renewable", then accordingly this criterion takes only two values 0 or 1. The transformation of indicators for constructing a spider diagram, namely the normalization of values by the selected criteria, was carried out according to the formula below:

$$\text{NormalizedValue} = \frac{\text{CurrentValue} - \text{Minimum}}{\text{Maximum} - \text{Minimum}}. \quad (1)$$

RESULTS AND DISCUSSIONS

GHG emissions and energy efficiency

In their study, Delivand & Gnansounou (2013) reported that compared to fossil diesel and gasoline, the life cycle GHG emission reductions for biodiesel could be 76.9–79.3% and 83.7–88.6%, respectively. For palm oil biodiesel production, the largest contribution to GHG emissions comes from the planting stage at 90%, where 29.8% and 23.2%, respectively, come from emissions from nitrogen fertilizer use and land use change (pesticides and herbicides do not make a significant contribution); in crude palm oil production, emissions account for about 1.1% of the total life cycle and about 8.8% of emissions come from the processing of palm oil into biodiesel (Paminto et al., 2022). Castanheira & Freire (2017) found that there are controversies regarding the choice of fertilization scheme to reduce environmental impacts. The authors report that calcium ammonium nitrate contributed to the highest GHG intensity, while ammonium sulphate and poultry manure contributed the lowest emissions. Biogas captured and burned at the oil extraction plant instead of being released to the atmosphere had the lowest impact across all categories (GHG intensity was reduced by over 60% when biogas was burned instead of released). At the agricultural stage, oil palm plantations typically use conventional diesel fuel for tractors transporting fertilizers and pesticides, as well as moving FFB from plantations to processing plants for palm oil production and waste back to the plantations. Carbon dioxide emissions associated with the use of fossil fuels in the life cycle of biodiesel production are second only to palm oil, which includes the contribution from the production and delivery of fertilizers of approximately $6.49 \cdot 10^{-3}$ gCO_2-eq/MJ (calculated from tons of gCO_2-eq/ton of palm oil) (Reijnders & Huijbregts, 2008).

About 16.8 gCO_2-eq/MJ (or 119 $kgCO_2$-eq) is the GHG emission from the production of 1 ton of fresh oil palm fruit bunches (FFB) according to the results of Choo et al. (2011). The use of large-scale biodiesel plants is associated with emissions of 468 $kgCO_2$-eq/ton FFB, which is approximately 62 gCO_2-eq/MJ if we assume for the sake of conversion that 1 ton of FFB can produce about 200 kg of biodiesel with an energy value of approximately 37–38 MJ/kg (Anyaoha & Zhang, 2023). The production of 1 ton of crude palm oil (CPO) in the plant without and with biogas capture emitted 25.9 gCO_2-eq/MJ and 13.5 gCO_2-eq/MJ (971 and 506 $kgCO_2$-eq), respectively; the production of 1 ton of refined palm oil in the plant that received CPO from the plant without and with biogas capture, the GHG emissions are approximately 29.68 gCO_2-eq/MJ and 16.69 gCO_2-eq/MJ (which can be written as 1113 kg and 626 $kgCO_2$-eq), respectively (Choo et al., 2011). Meanwhile, processing in semi-mechanized and small-scale plants reduces the environmental load by 44% (i.e., emissions are 34.7 gCO_2-eq/MJ) if palm oil mill effluent (POME) is converted to biogas and used instead of traditional diesel in transport, or a 75% load reduction is possible (i.e., emissions are 15.5 gCO_2-eq/MJ) if empty fruit bunch (EFB) composting is applied using POME wastewater (Anyaoha & Zhang, 2023; Choo et al., 2011). For palm biodiesel, emissions are 33.19 and 21.20 gCO_2-eq/MJ of biodiesel produced from palm oil obtained in the plant without biogas capture and with biogas capture, respectively (Choo et al., 2011). Indeed, some biofuel production technologies that replace traditional fuels with waste biomass can reduce GHG emissions (Kaliyan et al., 2011), and additional CO_2 capture from the plant's fermentation tank and carbon storage makes the process even more efficient, reducing emissions by approximately 18.4 gCO_2-eq/MJ when accounting for land use change (Kaliyan et al., 2011; Xu et al., 2022). As shown by the Malaysian palm oil mills, there is only a 16% chance of reducing GHG emissions by 35% and only a 3.7% chance of reducing emissions by 50% compared to fossil fuel use (Abdul-Manan, 2017).

Taking into account other biomass sources available in Nigeria for biofuel production, various studies report that rice husk and cassava biofuels also contribute to significant reduction in greenhouse gas emissions by about 6% compared to fossil fuels (Nguyen & Gheewala, 2008). These life cycle emissions are generally within the requirements of Directive 2018/2001 and range from 10 to 30 gCO_2-eq/MJ for the production-transport-combustion cycle. In comparison, maize biomass biofuels are reported to have GHG emissions of 50 – 60 gCO_2-eq/MJ without land use change and 80 – 105 gCO_2-eq/MJ with land use change (Rogowska & Wyrwa, 2021). The study (Xu et al., 2022) reported that emissions were reduced to 45 gCO_2-eq/MJ (by 13 units) without taking into account land use change due to the low energy consumption in the bioethanol production process and the low energy intensity of growing the feedstock.

At the same time, the use of fossil fuels such as diesel and natural gas contributes to emissions of 55 to 105 gCO_2-eq/MJ (Adeyemi, 2023), although according to the ICCT, for every MJ of diesel, 27.4 gCO_2-eq/MJ are emitted, but it should be emphasized that this value is given for a shorter WTT cycle, that is, "from well to tank", namely production-refining-transportation (Bieker, 2021). According to a study conducted at the LOTOS refinery in Gdansk, Poland, GHG emissions at different stages of the diesel fuel life cycle are: oil production: 4.83 gCO_2-eq/MJ; oil transportation: 0.88 gCO_2-eq/MJ; fuel transportation (by rail for 250 km): 0.16 gCO_2-eq/MJ; storage in tanks: 0.11 gCO_2-eq/MJ; delivery to filling stations and sale: 0.75 gCO_2-eq/MJ; combustion in the engine: 73.25 gCO_2-eq. Thus, the total GHG emissions at all stages are approximately 79.98 gCO_2-eq/MJ. It is important to understand that many factors influence the emission volumes, and first of all, the refinery layout, etc. Therefore, for the purpose of comparing different types of fuel in terms of GHG emissions, the observed trend should be considered rather than the exact figures (Rogowska & Wyrwa, 2021).

The results of the studies indicate that the use of low-emission fuel oils is an effective way to reduce GHG emissions during the life cycle of motor fuels. Such significant reductions in greenhouse gas emissions highlight the potential of bioenergy as a sustainable energy alternative. However, the energy return on investment (EROI) of bioenergy is often less favourable compared to fossil fuels, indicating a greater need for energy input to achieve an equivalent useful product. This highlights the need for bioenergy conversion technology development to improve process efficiency while maintaining their environmental benefits.

Energy efficiency analysis of some processes in the life cycle of oil palm biodiesel shows that significant amounts of steam and electricity are required at the stage of palm oil processing for CPO production. At the same time, by-products such as fibre and shell can be used as a source of steam and electricity through combustion and electricity recovery. This approach makes the palm oil production process self-sufficient in terms of electricity consumption. Thus, the authors Husain et al. (2003), based on data obtained from several palm oil plants, report 55.0 – 76.6% of the energy (steam and electricity) generated from fibre and shell to support the milling processes. If we assume that an average CPO plant uses 65.8% of such energy, then the equivalent energy consumption of the plant at this stage will be approximately 0.291 MJ of energy to obtain 1 MJ of energy from biodiesel (or 10.3 GJ/ton of CPO) (Husain et al., 2003). This means that the energy efficiency at this stage is approximately 29.1% of the output energy, which is a fairly acceptable cost, although there is still potential for reducing energy costs.

During the growth process, palm trees accumulate carbon in their own woody biomass and in the fruits, from which palm oil and then biodiesel are produced. These production processes are accompanied by some CO_2 emissions due to their energy needs, and the direct use of biodiesel provides emissions of previously absorbed CO_2, which is quite close to a closed cycle. In this regard, biodiesel from palm oil is considered a "clean" sequestration of CO_2 from the atmosphere, contributing to a decrease in the overall level of GHG relative to fossil fuels (Yee et al., 2009; Siangjaeo et al., 2011). At the same time, an equally important aspect is the irrational use of land, namely deforestation, and, as a result, a decrease in biodiversity.

Land and water use

The unintentional land use change from carbon-rich non-agricultural land to carbon-poor agricultural land in order to use biomass for biofuel production is an intermittent land-use change (ILUC). Achten et al. (2010) found that land use conversion to oil palm is associated with a significant decrease in ecosystem quality (EQ), namely by 30 – 45% compared to the potential of natural vegetation. Also, the scenarios studied by Achten et al. (2010) show an increase in the carbon debt with land use change even if the reduction in high global warming potential greenhouse gas emissions due to the use of biofuels from biomass does not offset this positive effect. And according to the mentioned study, the carbon debt for 45 – 53 years can neutralize the decrease in global warming potential (GWP) and an increase in eutrophication potential (EP) is observed compared to the reference fossil fuel. Similar results were obtained by Kusin et al. (2017) where it is reported that relatively higher levels of CO_2 emissions were observed due to the conversion of tropical forests to oil palm plantations, which amounted to more than 50% compared to if rubber plantations were converted, which contributes to an increase in emissions by 20%. However, regardless of the land conversion options, emissions range from 3.34 to 3.96 gCO_2-eq/MJ with an average yield of 4 ton of oil/ha. A number of studies have confirmed that the use of degraded or low-carbon lands (pasture, former cropland) is the most effective way to reduce the carbon footprint of palm oil biodiesel. Since the conversion of peatlands and tropical forests to oil palm cultivation has the highest emissions with offsetting needs lasting hundreds of years, indirect land use change through global demand (ILUC) is a major contributor and is amplified in the absence of rational planning, using agricultural or degraded land for oil palm cultivation produces lower emissions (Delivand & Gnansounou, 2013).An analysis of the financial aspects of biodiesel implementation in the Nigerian economy allowed the researchers to identify some financial levers of control. Thus, Okoro et al. (2018) report that a significant amount of emissions can be reduced by introducing a tax on GHG emissions, regardless of whether there is a subsidy for bioenergy production or not. However, support for the bioenergy industry does not have a significant impact on Land Use Change (LUC) emissions, including those from deforestation, agriculture, construction, and other land use changes that affect the absorption and emission of greenhouse gases. Unfortunately, it turned out that land use change limitation strategies based on GHG taxes are not effective in preserving ecosystems in Nigeria. The results of regional estimates of GHG emissions associated with LUC due to the expansion of palm oil production for biodiesel in different regions of Nigeria are presented in Table 3.

Table 3. Energy return on investment (EROI) comparison

Source	Geographical area	LUC emissions, gCO_2-eq/MJ	Key findings
Acobta et al., 2023	Southern Nigeria (Cross River, Edo), rainforests	40 – 65	High carbon in biomass, clearing of primary forests
Wang et al., 2025	Central Nigeria (Benue, Kogi), savannahs and shrublands	15 – 30	Medium carbon density; clearing of secondary lands
Anyaoha & Zhang, 2023	Degraded/agricultural land	10 – 20	Shifting from already used agricultural land, low emissions
Persson et al., 2014	ILUC – indirect emissions	10 – 30	Shifting food crops to other regions/countries
Manik & Halog, 2013	Methodology/benchmarking	< 60 at primary conversion	Methodology for estimating emissions from land use change

Table 4. Summary of water use in the life cycle of oil palm biodiesel in Nigeria

Source	Life cycle stage	Water footprint, m^3/L biodiesel	Key findings
Nilsalab et al., 2017	Agriculture (sowing, palm growing)	4 – 9	Example from Thailand; about 99% of all water consumption is at this stage
Kittithammavong et al., 2014	Industrial production (transesterification and purification)	≈ 0.012	Sterilization, purification, transesterification with methanol and glycerine
Kospa et al., 2017	Growing and processing (Indonesia data)	≈ 3.8 (≈980 m^3/ton)	Water accounting at all stages from the field to the output of finished oil and wastewater
Generalization based on Thailand and Indonesia	Assessment in the Nigerian context (summary)	4 – 10	Total value by analogy with regions with a tropical climate and an irrigation system

Water use in palm oil production is variable, affecting the growth and activity of microorganisms, primarily methanogens, contributing to high and volatile GHG emissions. It is estimated that for every ton of oil palm fruit bunches, 0.5 – 0.75 ton of palm oil mill wastewater containing around 5 kg/ton of organic matter will be discharged into the palm oil mill wastewater. Treatment is mainly carried out using ponds and/or open digestion systems (Reijnders & Huijbregts, 2008). On average, biogas production in a typical palm oil mill wastewater treatment pond is 0.5 – 2.4 L/min/m^2 with a methane content of 35% – 70%. In Nigeria, direct studies describing water use specifically for palm biodiesel are extremely limited, but based on LCA studies from similar regions, the water requirement for biodiesel production is 4 – 19 m^3/L biodiesel or equivalent to 0.142 m^3/MJ, of which approximately 99% of the water is consumed at the agricultural stage as irrigation water for oil palm cultivation (Nilsalab et al., 2017; Arguelles-Arguelles et al., 2021). Considering the similar tropical climate and agricultural practices, the given values can be roughly taken for Nigeria (Table 4).

To put into perspective the potential for renewable energy from biomass available in Nigeria, Figure 5 provides a comparative analysis of water consumption for other crops with energy potential. Figure 5 clearly shows that maize and sugarcane are the leaders in water consumption, and importantly for Nigeria in the context of water scarcity, fossil fuels do not require large volumes of water consumption. Some notes on land use and water use for different types of biomass available in Nigeria are presented in Table 5.

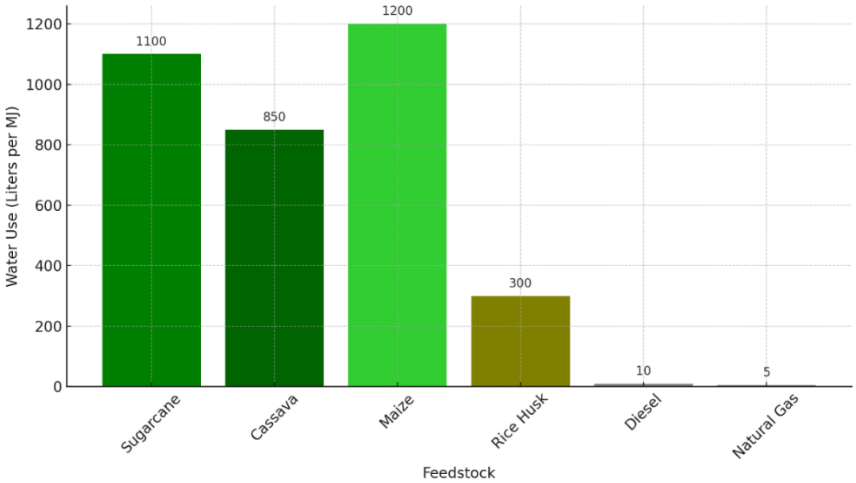

Figure 5. Water use per 1 MJ of energy from different feedstocks

Table 5. Summary of land and water use for major biomass types in Nigeria

Feedstock	Land use, ha/GJ	Water use, L/MJ	Notes
Cassava	0.15 – 0.25	700 – 1.200	Widely grown in Nigeria; moderate yield; relatively high water footprint
Sugarcane	0.10 – 0.20	1.100 – 3.000	High ethanol yield but extremely water-intensive; irrigation-dependent
Maize	0.12 – 0.22	900 – 1.400	Competes with food supply; high water requirement
Rice Husk	0.05 – 0.10	200 – 400	Agro-waste; low land requirement; low water use
Palm Oil Waste	0.08 – 0.15	300 – 700	Utilizes residues from oil processing; moderate water intensity
Diesel (fossil)	Negligible	~10	Minimal land use; water used mainly in processing and refining
Natural Gas	Negligible	~5	Very low land and water impact; emissions-intensive

Human toxicity and socio-economic effects

Human toxicity refers to potential adverse health effects from oilseed biodiesel production. The agricultural stage of oil palm cultivation is accompanied by the intensive use of insecticides, herbicides and fertilizers, including heavy metals, which in turn reduces environmental quality and provokes endocrine disruptions, reproductive toxicity and chronicity of diseases with long-term exposure. The main pathway for the manifestation of such risks is the food chain (Alengebawy et al., 2021; Arguelles-Arguelles et al., 2021). The increased risks of water-borne diseases are associated with erosion and changes in hydrology due to agrochemical runoff. The negative consequences of such effects on the population of Nigeria are reported in a study (Izah et al., 2016), namely, above-normal levels of air and water pollution. At the same time, the reduction of PM, carbon monoxide and hydrocarbons from burning oil biofuels compared to fossil diesel helps reduce respiratory diseases in the population, especially in urban environments or areas close to emission sources (Suhara et al., 2024). Overall, although bioenergy can mitigate the effects of specific pollutants, its health benefits depend on clean production methods and effective emissions management. Life cycle analysis shows that, when responsibly managed, bioenergy generally has lower long-term toxicity to humans compared to fossil fuels (Figure 6).

Fossil fuels consistently exhibit elevated human toxicity potential throughout life cycle assessments, attributable to the emissions of hazardous pollutants including sulphur dioxide, nitrogen oxides, particulate matter, and volatile organic compounds during extraction, refining, and combustion phases (UNEP, 2022). These pollutants substantially contribute to respiratory and cardiovascular ailments, particularly in densely populated or industrial regions.

The geographical distribution of bioenergy pilot sites in Nigeria was developed by Ukoba et al. (2024) (Figure 7) and the socio-economic effects of using bioenergy compared to fossil fuels are shown in Table 6.

By-products and their uses

Approximately 10 – 11% of glycerol is generated from the mass of biodiesel produced from palm oil (Yang et al., 2012), which is a by-product that can be separated and used in the production of detergents or cosmetics, and also used to produce xylitol by adding crude glycerol to Candida tropicalis

(NCIM3118) (Chatterjee et al., 2015; Sanjana et al., 2024). The seed cake remaining after extraction is valuable as a biofertilizer (Chatterjee et al., 2015). Currently, Empty Fruit Bunches (EFB) are mainly used as mulch in oil palm plantations to control weeds, prevent erosion and maintain soil moisture.

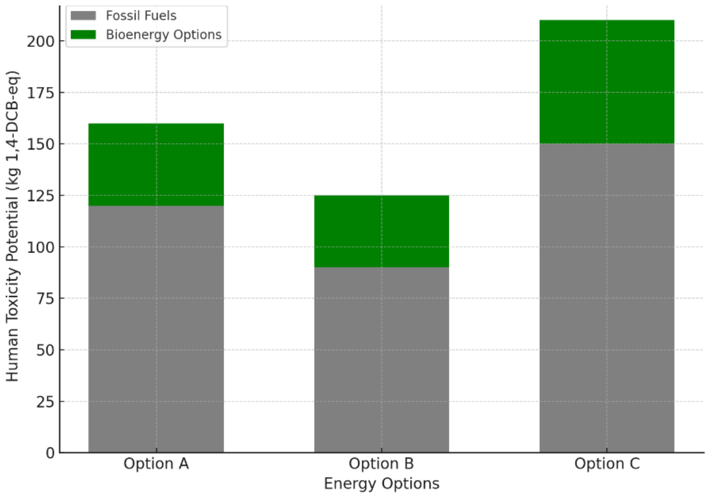

Figure 6. Human toxicity potential comparison

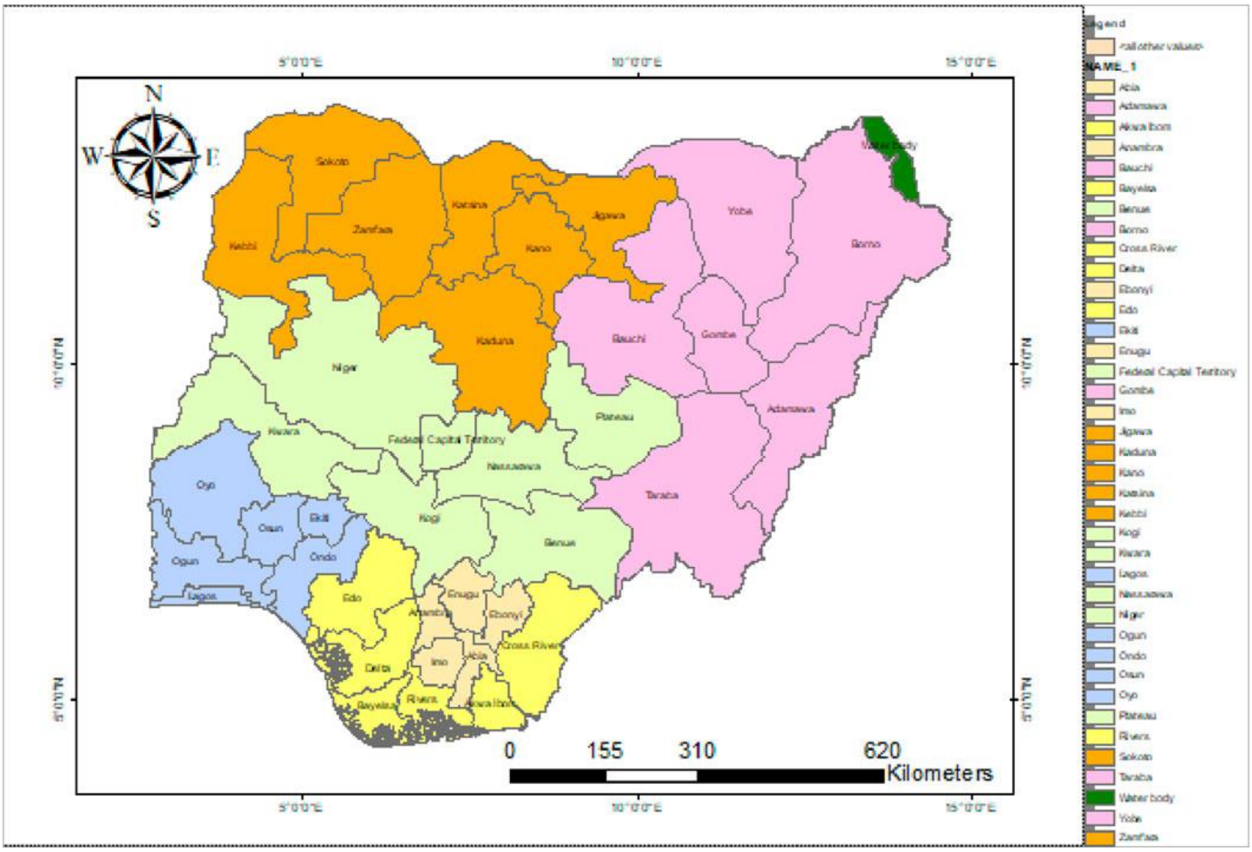

Figure 7. Case study map: community-scale bioenergy projects in Nigeria
(Ukoba et al., 2024, *Creative Commons Attribution License International CC-BY 4.0*)

Table 6. Socio-economic effects of bioenergy vs fossil fuels in rural Nigeria

Effect	Bioenergy	Fossil fuels
Number of tasks per TJ	Up to 60 jobs/TJ (oil palm, cassava, sugar cane)	1 – 5 works/TJ (mainly in distribution)
Fuel savings	Moderate to high (local raw materials, reduced transport costs)	Low to moderate (price volatility, import dependence)
Energy access levels	High (through decentralized mini-grids)	Limited (grid dependent, unreliable power supply)

If we consider, summarize, all the studied indicators and average the values without going into deep details of each life cycle – biofuel and traditional fuel, then the comparative results look as presented in Table 7. The interpretation of the results is presented graphically in Figure 8 for the studied indicators of comparison of biofuels and conventional fuels per 1 MJ of useful energy. For the six comparison categories, the negative metrics (GHG, input energy, water, acidity, waste) were inverted and normalized to a 0 – 1 scale in order to identify the best value (Table 8). Figure 8 shows that palm biodiesel outperforms conventional diesel in 2 of 6 key categories: sustainability and GHG emissions. At the same time, conventional diesel requires less water throughout its life cycle, requires less energy to produce, and produces less waste.

Table 7. Comparison of the main studied indicators of the life cycle of two types of fuel

Indicator	Biofuel	Traditional fuel
Raw material source	Agricultural waste	Fossil fuels
Renewability	Yes	No
GHG emissions (CO_2-eq)	20 – 40 g	74 – 90 g
Energy costs of production	0.3 – 0.5 MJ	0.1 – 0.2 MJ
Energy efficiency (EROI)	~ 2 : 1	~ 5 : 1
Water consumption	1 – 2 L	< 0.1 L
Acid/toxicity	Moderate (H_2SO_4, neutralizers)	High (NO_x, SO_2 during combustion)
Waste generation	Lignin, wastewater	Partial soot, emissions
Combustion emissions	Biogenic CO_2, low NO_x and particulate matter	CO_2, NO_x, PM, SO_2
Supply stability	Varies with season and region	Developed global logistics
Employment/rural development	Stimulates	Does not stimulate
Infrastructure compatibility	Partial (adaptation needed)	Full

Table 8. Estimated numerical values per 1 MJ of useful energy in the Nigerian context

Comparison category	Palm biodiesel (Nigeria)	Conventional diesel (Nigeria, average)	References
GHG emissions (gCO_2-eq/MJ)	45	110	Anyaoha & Zhang, 2021; Somorin et al., 2017
Energy consumption (MJ/MJ input)	0.40	0.12	Anyaoha & Zhang, 2021
Water consumption (L/MJ)	80	6	Igbosoroeze & Okojie, 2024
Acid/toxic impact (kg SO_2e eq average)	0.00035	0.00025	Igbosoroeze & Okojie, 2024
Waste generation (relative, normalized)	0.7	0.2	Anyaoha & Zhang, 2021
Renewability	1.0	0.0	Isah et al., 2025

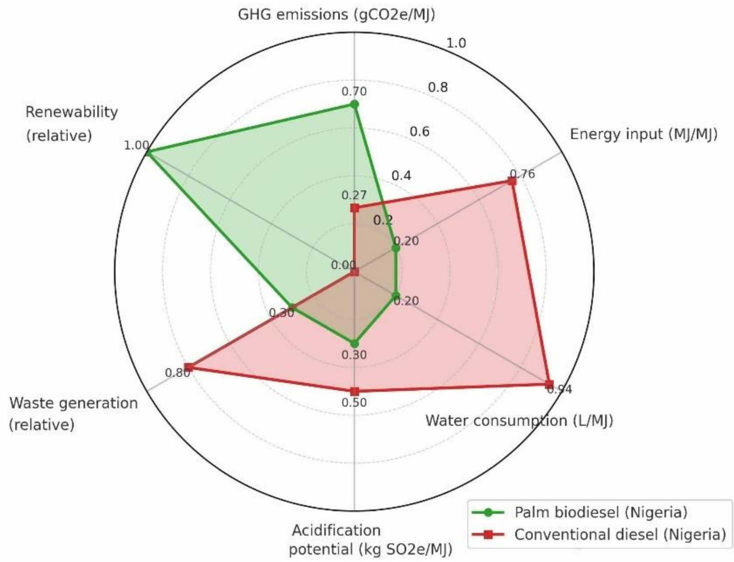

Figure 8. Interpretation and visualization of life cycle assessment of two types of fuels

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CONCLUSION

The lifecycle assessment of bioenergy systems compared to fossil fuel alternatives provides critical insights for shaping sustainable energy transitions in Nigeria. While fossil fuels have historically powered the nation's economy, their environmental and health impacts underscore the urgent need for cleaner alternatives. Bioenergy, with its potential to reduce greenhouse gas emissions, promote rural development, and utilize locally available biomass resources, presents a promising pathway toward sustainability.

However, the benefits of bioenergy systems are highly dependent on feedstock selection, land use practices, and processing technologies. A comprehensive life cycle perspective reveals that, when sustainably managed, bioenergy systems can significantly outperform fossil fuels in terms of environmental impact, particularly in reducing carbon intensity and enhancing energy security.

For Nigeria, integrating bioenergy into the national energy mix requires supportive policies, investment in research and infrastructure, and robust sustainability criteria to avoid unintended consequences such as deforestation or food insecurity. By aligning energy planning with lifecycle-based insights, Nigeria can move toward a resilient and inclusive energy future that supports both environmental goals and socio-economic development.

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Author's statements

Contributions

Conceptualization: M.A.A., M.A.O.; Data curation: S.C.E.; Formal Analysis: E.N.N.; Investigation: M.A.O., I.D.O.; Methodology: A.B.M.; Project administration: J.O.I.; Resources: F.O.E.; Supervision: O.A.O.; Validation: C.A.; Visualization: S.B.J.; Writing – original draft: J.O.I., M.A.O.; Writing – review & editing: B.E.A.

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The authors declare no competing interests.

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