Clean Technologies and Recycling

Clean Technologies and Recycling, 3(2): 92–106.
DOI: 10.3934/ctr.2023006
Received: 21 February 2023
Revised: 01 April 2023
Accepted: 06 April 2023
Published: 20 April 2023

http://www.aimspress.com/journal/ctr

Mini review

Biodiesel: Analysis of production, efficiency, economics and sustainability in Nigeria

Chidiebere Millicent Igwebuike*

IMT Atlantique, GEPEA, UMR CNRS 6144, 4 rue Alfred Kastler, F-44000 Nantes, France

* **Correspondence:** Email: chidieberem.igwebuike@gmail.com.

Abstract: Biodiesel, a type of biofuel is a low-carbon substitute for fossil fuels. It has a flash point of 100 to 170 °C and an energy content of 33 MJ/L and can help to mitigate climate change by reducing greenhouse gas emissions. This review looked at the properties and benefits of biodiesel and the current situation of Nigeria's biodiesel industry. It examined the various feedstocks, including first-, second-, third- and fourth-generation options, and assesses their availability, viability and cost. The assessment analyzed the industry's challenges as well as the policies and incentives for biodiesel production, and use in Nigeria. Taking into account the cost of production, distribution and use, as well as prospective government subsidies and tax credits, the economic viability of biodiesel was also evaluated. Generally, the biodiesel industry in Nigeria has the potential for growth with the right assistance from the government and private sector.

Keywords: biofuel; biodiesel; feedstocks; policies; challenges; social and environmental impact

1. Introduction

Currently, emphases have been shifted to the use of locally sourced materials for the production of renewable fuels. Biofuels are renewable energy sources produced from plant or animal materials. They are believed to be viable alternatives to fossil fuels (e.g. crude oil, coal and natural gas). For more than 150 years, fossil fuels have been fueling economies, and they now provide nearly 80% of the world's energy. Fossil fuels are well-known for releasing stored carbon and other greenhouse gases into the atmosphere when burned [1]; 73% of the CO_2 emission is caused by the burning of fossil fuels [2]. The EIA-Energy Information Administration projects an almost 50% increase in global energy use by 2050, led by growth in renewables [3]. An increase in human population and industrialization means an increase in fossil fuel utilization and an increase in environmental waste generation. However, these challenges could be curbed if more transitions to renewable energy sources are observed [4]. Biodiesel is one of the most commonly produced biofuels and it is also referred to as fatty acid methyl ester (FAME). It is a clean-burning fuel made by transesterifying triglycerides, which are the major component of different feedstock oils like fresh and used vegetable oil including oil from algae and animal fat, with alcohol in the presence of a catalyst [5]. Biodiesel contains an energy content of 33 MJ/L [6] and it is used to power compression-ignition (diesel) engines, just like petroleum-based diesel. Biodiesel can be used in pure form (B100) or it can be mixed with petroleum fuel in any ratio such as B2 which represents 2% biodiesel and 98% petroleum diesel, B5 which denotes 5% biodiesel and 95% petroleum diesel, and most popular blend, B20 which is a blend comprising 20% biodiesel and 80% petroleum diesel [7]. In Nigeria, biodiesel production has the capacity to strengthen the nation's energy security and benefit local communities economically. The sector does, however, face some difficulties, such as technological constraints, financial viability and social and environmental implications [8].

The country has a large agricultural sector which validates its potential for biodiesel production. Despite this, the biodiesel industry remains underdeveloped, and there is a knowledge gap regarding its current situation. Comprehensive studies on the availability, viability and cost of different feedstocks, as well as the economic viability of biodiesel production, distribution and use in the nation are lacking. Furthermore, the challenges facing the industry such as issues with feedstock quality and processing, have not been thoroughly investigated, and the social and environmental impacts of biodiesel production and use in Nigeria have not been sufficiently evaluated [9,10]. To fully understand the potential of biodiesel in Nigeria and create effective policies and strategies to encourage its expansion, it is imperative to address these knowledge gaps. The goal of this literature study is to give an overview of the Nigerian biodiesel sector as it currently stands. The evaluation will examine the properties and benefits of biodiesel, prospective biodiesel feedstock, government regulations and incentives for the sector and the sustainability of the biodiesel industry. The evaluation will also look at the challenges the sector is now facing as well as the social and environmental effects of biodiesel use and production in the country.

2. Properties of biodiesel

The characteristics of biodiesel give a clue as to whether or not it would be appropriate for the engine's performance, longevity and emissions [11]. Biodiesel's poor qualities at low temperatures and its low oxidation stability are the two main issues that need to be resolved in order to use it. These come about as a result of the physical and chemical characteristics of the principal biodiesel constituents, fatty acid methyl esters (FAME), as well as certain other minor constituents that form during the transesterification process. Cetane number, viscosity, cloud point, pour point, cold filter plugging point (CFPP), specific gravity, flash point, iodine value and heating value are important characteristics that are directly related to FAME and are some of the properties of biodiesel that distinguish it from petroleum-based diesel [12].

The cetane number is a measure of how well a fuel ignites. The higher the cetane number, the more efficiently a car's engine burns fuel. Viscosity is a measure of the thickness or resistance to flow of the liquid fuel. The lower the viscosity of the fuel the better to allow for better flow and combustion [13]. The cloud point is the temperature at which a fuel begins to solidify i.e. the temperature at which wax crystals begin to form in the fuel. The lower the better because a higher cloud point can result in clogging of fuel filters and poor cold weather performance. Pour point is the temperature at which fuel ceases to flow. A lower pour point allows the fuel to flow more easily in cold temperatures. CFPP is the lowest temperature at which the fuel will pass through a standardized filter. A lower CFPP gives an indication that the fuel can be used at lower temperatures without clogging the fuel system [14]. Specific gravity is the density of biodiesel compared to the density of water [15]. The flash point is an indicator of a fuel's combustibility or flammability. Simply put, flash point is the temperature at which a fuel will ignite when exposed to a spark or flame. Compared to petroleum-based diesel, biodiesel has a higher flash point which means it is less flammable [16]. The iodine value is an indicator to examine the degree of unsaturation or the number of double bonds in the fatty acid chains. A lower iodine value indicates that the fuel has higher oxidative stability, and hence, is better for storage and use [17]. Heating value is the amount of energy released when a fuel is burned. A higher heating value indicates a greater amount of energy available for use [18]. Some characteristics of biodiesel and No. 2 diesel fuels are given in Table 1.

Table 1. Comparison of the properties of biodiesel and petroleum-based diesel (No. 2 diesel) [19].

Properties	Biodiesel	Diesel
Standard	ASTM D6751	ASTM D975
Cetane number	47 to 65	40 to 55
Kinematic viscosity, @ 40 °C	4.0 to 6.0	1.3 to 4.1
Cloud point, °C	−3 to 15	−35 to 5
Pour point, °C	−5 to 10	−35 to −15
Specific gravity @ 15.5 °C	0.88	0.85
Density, lb/gal @ 15.5 °C	7.3	7.1
Flash point, °C	100 to 170	60 to 80
Higher heating value, Btu/gal	~127960	~138490
Lower heating value, Btu/gal	~119550	~129488
Boiling point, °C	315 to 350	180 to 340
Carbon, wt%	77	87
Hydrogen, wt%	12	13
Oxygen, by dif. wt%	11	0
Sulfur, wt%	0.0 to 0.0015	0.0015 max.

3. Benefits of biodiesel as a renewable energy

Governments in the majority of industrialized nations encourage the use of renewable resources and energies with the following key objectives: (i) to secure access to energy, (ii) to mitigate climate changes, (iii) to develop/maintain agricultural activities and (iv) to ensure food safety [20]. Table 2 highlights some of the advantages of biodiesel production and utilization.

Table 2. Benefits of biodiesel [21–23].

	Benefits	Highlight
1	Generated from renewable resources	Unlike petroleum fuels, which will run out in the future, biodiesel is a source of sustainable energy. It can be made on demand and emits less pollution than petroleum diesel because it is made from animal and vegetable fat.
2	Reduced emissions of greenhouse gases	Burning fossil fuels releases greenhouse gases into the atmosphere, such as carbon dioxide, which elevates temperatures and contributes to global warming. Embracing biofuel usage could to a great extent prevent the environment from further warming. Switching to biodiesel can lower net CO_2 emissions by up to 78.45%.
3	Adaptable to current compression-ignition engines	The ability to use biodiesel in current diesel engines with minimal or no modifications is one of the fuel's key benefits. Diesel made from petroleum can be easily combined with biodiesel which has excellent lubricity properties. In contrast to diesel fuel, it does not require sulfur for lubrication. Biodiesel is almost entirely sulfur-free and thus results in reduced pollution. The oxygen in biodiesel is what provides the fuel with its lubricity properties. The petroleum diesel is given the necessary lubricity with as little as 2% biodiesel added (a B2 blend), and greater blends help add much more lubrication.
4	Decreased reliance on imported oil	Most nations have lessened their reliance on fossil fuels thanks to locally produced biofuels. A country could save fortunes by lowering its reliance on imported oil.
5	Safer fuels than fossil fuels	Biodiesel is far less harmful than conventional diesel if spilled or discharged into the environment. Biodiesel has a higher flash point (150 ℃) than petroleum diesel (55–66 ℃). As a result, compared to biodiesel, petroleum is significantly more inflammable and hazardous.

4. A brief on Nigeria's biodiesel industry

Nigeria's biodiesel sector is still in its early phases of development but has enormous growth potential. Nigeria currently has a small capacity for biodiesel production, but interest in the sector and investment have recently increased. The primary raw materials used to make biodiesel in Nigeria are palm oil, jatropha and other regionally cultivated crops. The most extensively utilized feedstock is palm oil because of its vast availability and moderate price. Jatropha has also drawn interest as a potential feedstock for biodiesel because of its high oil content and ability to grow in adverse conditions [24].

The growing interest in sustainable living and renewable energy is fueling an increase in the market demand for biodiesel in Nigeria. However, at the moment, Nigeria's demand for biodiesel is constrained by a lack of infrastructure, distribution methods and consumer knowledge and comprehension of the fuel's advantages. The government of Nigeria has put laws and incentives in place targeted at boosting biodiesel production and consumption in order to assist the industry's expansion in the country. In addition to rules aimed at boosting the use of biodiesel in the transportation sector, these policies also include tax credits and subsidies for the production of biodiesel [25]. Essentially, Nigeria's biodiesel industry is at present characterized by low production capacity, a wide range of feedstocks and rising consumer demand. Although there is the potential for significant future expansion, obstacles still need to be surmounted if Nigeria is to enable the emergence of a viable biodiesel industry [26].

5. Potential biodiesel feedstock in Nigeria

Four categories of feedstocks can be used to produce biodiesel: first, second, third and fourth-generation feedstocks. Biofuels from second, third and fourth-generation feedstock are called advanced biofuels. Certain factors have been outlined to influence the deployment of advanced biofuels and these include (a) the accessibility/availability of feedstock (b) access to capital, particularly for investments in the development and testing of novel technologies (c) the impact of policy and regulation (d) support for advanced biofuels market adoption (e) consumer confidence and (f) investor confidence [27]. Figure 1 gives a flow diagram of biodiesel production from the four categories of feedstocks.

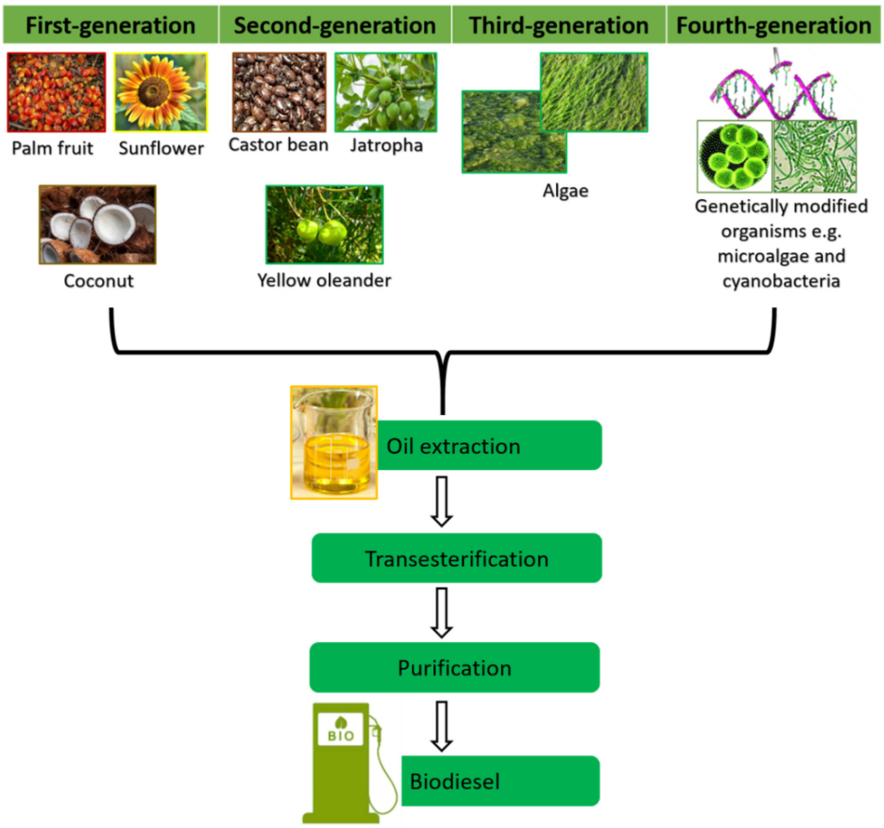

Figure 1. An illustration of biodiesel production process from first, second, third and fourth-generation feedstock [28].

5.1. First-generation feedstocks

Crops that have been extensively farmed for food production, such as palm oil, coconut oil, soybean oil, sunflower oil and rapeseed (canola) oil are examples of first-generation feedstocks [29]. These feedstocks are widely accessible in Nigeria. However, their use for biodiesel production has been challenged. The concern about using first-generation feedstocks comes from the fear that they can lower the production of food for consumption, and not for biodiesel production; they can compete with food production for land and resources, which can lead to higher food prices and food insecurity in some regions. In addition, the use of first-generation feedstocks for biodiesel can have negative environmental impacts, such as deforestation, habitat destruction and increased greenhouse gas emissions [30]. The drawbacks associated with the utilization of first-generation feedstock for biodiesel production have led to a growing interest in the development of second, third and fourth-generation feedstocks. These feedstocks aim to address these drawbacks to provide a more sustainable source of renewable energy [31].

5.2. Second-generation feedstocks

Crops that are cultivated solely for the purpose of generating energy and not for food are considered second-generation feedstocks [32]. Castor, jatropha, mahua, yellow oleander, tung and pongamia are examples of second-generation feedstocks [33]. These feedstocks have the benefit of having a low environmental effect and not competing with food crops, but farmers have several concerns growing them such as; the availability of land, dedicating land to a single crop for an extended period of time, the impact of energy crops on the quality of the land, relative financial return and cash-flow considerations and knowledge of or familiarity with the crop, etc [34]. Also, they are less accessible than first-generation feedstocks.

5.3. Third-generation feedstocks

Microalgae are considered the potential feedstock for the production of third-generation biodiesel. Microalgae have the potential to produce more oil per hectare of cultivated area compared to conventional biodiesel crops. Microalgae are unicellular organisms that can produce high quantities of lipids (oils) under the right conditions, such as high light intensity, temperature and the availability of nutrients like nitrogen and phosphorus. Some species of microalgae can produce oil content of up to 50% or more of their dry weight. The possession of high lipid content makes them one of the most promising feedstocks for biodiesel production [35]. Table 3 gives the yield of some feedstock considered for biodiesel production. Conventional biodiesel crops, such as soybean and rapeseed, typically have oil contents of about 20–42% of their dry weight [36–38]. This means that it would take more land to produce the same amount of oil compared to microalgae. Microalgae have the added advantage of being able to grow in a wide range of environments, including brackish water and wastewater, which are not suitable for conventional crops. This means that microalgae can be grown on non-arable land, avoiding competition with food crops. Nevertheless, for microalgae to be a viable and sustainable source of renewable energy, there are many technical and economic challenges that need to be addressed [39].

Table 3. The yield of various biodiesel feedstock [40,41].

Category	Feedstock	Oil yield (L/ha/year)	Biodiesel productivity (Kg/ha/year)
First-generation	Palm oil	5366	4747
	Soybean	446	562
	Rapeseed	1190	862
	Sunflower	952	946
Second-generation	Jatropha	1892	656
	Castor	1307	1156
Third-generation	Microalgae[a]	58700	51927
	Microalgae[b]	97800	86515
	Microalgae[c]	136900	121104

[a]30% oil by wt in microalgae; [b]50% oil by wt in microalgae; [c]70% oil by wt in microalgae.

5.4. *Fourth-generation feedstocks*

Fourth-generation feedstocks for biodiesel production are the most advanced but not yet widely adopted or commercialized as they are still in the development and experimental stages. They include genetically modified microorganisms such as microalgae and cyanobacteria [42]. These microorganisms utilize solar energy, water and CO_2 to produce biofuels. The number of steps required to absorb and convert solar energy into biofuels is reduced by genetically and metabolically modifying the microorganisms that can produce them. Genetic modification can also be used to increase the capture of CO_2 (thus decreasing emissions into the environment) and improve lipid production [43]. Biofuels from this category of feedstock are anticipated to have a significantly higher photon-to-fuel conversion efficiency in relation to other feedstock categories [32]. Presently, there are limited studies and research on the use of fourth-generation feedstocks for biodiesel production in Nigeria, and their viability and environmental impact are still being evaluated.

6. Assessment of availability, sustainability and cost of feedstock for biodiesel production

6.1. *Availability*

First-generation feedstocks like palm oil are readily available in Nigeria whereas second-generation feedstocks such as jatropha are still being developed and are not as widely grown. Third-generation feedstocks are also in the early phases of development. There are surprisingly few reports on the cultivation of microalgae in Nigeria. However, many of these microalgae species thrive in abundance in Nigeria's natural aquatic settings, particularly during the rainy season, in gutters, ditches, ponds, puddles, rivers, seas and oceans. In both wet and dry conditions in Nigeria, these organisms have been seen to spontaneously flourish. Furthermore, there have been some attempts to examine the potential of algae as a feedstock for the nation's biodiesel production and the outcomes thus far have been encouraging [44].

6.2. *Sustainability*

Second-generation feedstocks are thought to be more sustainable since they have a lesser environmental impact than first-generation feedstocks, which have been criticized for their negative effects on the environment, such as deforestation and biodiversity loss. Though second-generation feedstock and biodiesel production methods from these feedstocks are effective, if they compete with food crops for limited land, their production can become unsustainable. Therefore, the sustainability of their products will depend on how well producers adhere to requirements such as minimum lifecycle GHG reductions, including land use modification and social norms [45]. Of all, third-generation feedstocks are considered to be the most environmentally friendly option for biodiesel production as they have a low carbon footprint and do not compete with food crops for land and resources. Algae, for example, can be grown in open ponds or closed photobioreactors, which can be located on non-arable land, reducing the impact on agricultural land and wildlife [46].

6.3. *Cost*

In terms of cost, third-generation feedstocks are currently more expensive to produce when compared to first and second-generation feedstocks, as the technology and processes involved are still in the development stage. However, as technology improves and production processes become more efficient, it is expected that the cost of producing third-generation feedstocks will decrease [47].

In addition to the above, fourth-generation feedstock possibly have the potential for higher productivity than aforementioned generations. Nevertheless, the cost of production and their scalability may be a challenge, and their sustainability will depend on factors such as energy and resource inputs.

7. Government policies and incentives for biodiesel in Nigeria

The government has set various policies and incentives to aid in the development of the biodiesel sector, however, these policies are still not well established and not often effectively implemented. Government subsidies that aim to lower the cost of biodiesel production and stimulate the use of this renewable fuel, are one of the key motivations for the production and use of this fuel in Nigeria. These subsidies can take the form of financial assistance or tax credits for biodiesel producers, or direct subsidies to the end-users of biodiesel, such as transportation companies or farmers [48].

In addition to providing subsidies, the Nigerian government has also developed rules and specifications for the production and use of biodiesel. These rules seek to provide fair play for all biodiesel producers while also guaranteeing that the quality of biodiesel produced in the nation matches international standards. The Nigerian biodiesel sector is still in its infancy and hasn't yet reached its full potential despite these regulations and incentives. The industry is faced with some obstacles, such as a lack of investment and infrastructure, a lack of knowledge and understanding of the advantages of biodiesel, and a lack of loan availability for small and medium-sized biodiesel producers [49]. Nevertheless, there is tremendous room for expansion. The government should step up by creating successful policies and incentives in order to realize this potential. This entails working with industry stakeholders to address the issues preventing the sector's expansion and advancing the study and creation of environmentally friendly, sustainable biofuel technologies. The government should promote the use of biodiesel in transportation and other industries, as well as support private sector investment, to help the biodiesel industry grow even further. Easy availability to fuel will increase demand and open up business opportunities for farmers and entrepreneurs who can provide the raw materials for biodiesel production. This will be made possible by a well-established distribution network [50].

The biodiesel industry can as well benefit greatly from the support of private companies. They may aid in the development of the sector by making investments in cutting-edge technology and teaching people about the advantages of biodiesel and the necessity for sustainability in the energy industry [51]. In general, the interaction of governmental regulations and incentives, private sector investment and the creation of new technology will determine the success of the biodiesel industry in Nigeria; the biodiesel industry can expand and have a big impact on the nation's energy security and economic growth with the appropriate confluence of these factors.

8. Economic viability of biodiesel

The cost of production, distribution and use, as well as the availability of government subsidies and tax credits, are important considerations for determining the economic sustainability of biodiesel production and use in Nigeria [52].

(a) The cost of feedstocks, which can vary based on the type of feedstock and its availability, is one of the main factors determining the economic sustainability of biodiesel production. Feedstock like Jatropha can demand greater investment in terms of land and water resources, whilst feedstocks like palm oil, are easily accessible and relatively inexpensive.
(b) Another crucial element is the cost of production, which influences both the overall cost of biodiesel and its ability to compete with alternative fuels. The technology employed, the accessibility of production facilities and the price of raw materials can all have an impact on production costs.
(c) Regarding distribution, the cost of moving biodiesel from production facilities to end-users can have a substantial impact on the industry's overall economic viability. The creation of a strong distribution network becomes essential in expanding access to biodiesel and lowering transportation costs.
(d) The potential of government subsidies and tax breaks can affect how economically viable biodiesel production and use in Nigeria are. The use of tax credits and government subsidies, for instance, can encourage investment in the sector and increase the use of biodiesel as a fuel source while also helping to offset production costs and increase biodiesel's competitiveness with other fuels.

For the biodiesel sector in Nigeria to be successful over a long term, it is essential to conduct a detailed analysis of the costs and benefits of production and use [53].

9. Challenges for biodiesel development

Biodiesel development faces difficulties everywhere in the world. In developing nations, these difficulties are far more pronounced. The quality of feedstock is one of the challenges the biodiesel sector in Nigeria faces. The composition of the feedstock, the amount of free fatty acids and the water concentration have all been found to have an impact on the yield and quality of biodiesel. However, the production methods employed determine how much of an impact this effect has [54]. In essence, the effectiveness of processing and the general quality of the finished product can both be impacted by the quality of the raw materials. To overcome these challenges, it is crucial to make investments in the research and development of feedstock production technologies as well as establish quality control procedures to guarantee feedstocks adhere to the requirements for the production of biodiesel.

The effectiveness of processing is another significant issue the Nigerian biodiesel company is confronted with. There may be production bottlenecks that affect the overall efficiency and cost-effectiveness of biodiesel production. The processing of feedstocks into biodiesel requires specialized equipment and technical know-how. It is crucial to make investments in new processing technologies and to collaborate with stakeholders to develop more efficient production methods in order to overcome these obstacles [55]. Broader environmental and sustainability concerns should also be addressed when considering the development of the biodiesel industry in Nigeria. For instance, using first-generation feedstock may have negative impacts on the environment and biodiversity, raising questions about the long-term viability of these resources [56]. The lack of adequate manpower and expertise in the biodiesel industry in Nigeria has been identified as a factor also limiting its development. This can impact the quality of feedstock, processing and production and hinder the growth of the industry. In order to overcome these challenges, it is important to invest in human capital development, provide training and education to workers, and encourage the development of local expertise in the field. Additionally, collaboration with international organizations and institutions could also help to bring in the necessary technical knowledge and expertise to help the industry overcome these challenges and achieve sustainable growth in the future [57].

Other competing economic difficulties facing the developing countries as well as lack of political will on the side of the government and policymakers are also recognized obstacles to the rapid development of biodiesel in the country [58].

10. Social and environmental impact of biodiesel

When assessing the feasibility of the industry, it is crucial to take into account the social and environmental effects of biodiesel production and use. Impacts on land use are one of the key issues since growing feedstocks for biodiesel production might displace other crops and cause deforestation. This could affect local communities by causing a loss of resources and land, as well as lead to the extinction of species and other environmental problems [59]. The effect of biodiesel production on greenhouse gas emissions should also be taken into account. Although biodiesel is promoted as a more environmentally friendly substitute for fossil fuels, the production can nevertheless cause greenhouse gas emissions through the cultivation and processing of the feedstocks. It is crucial to carefully analyze the lifecycle emissions of biodiesel and to take action to reduce these emissions, such as choosing sustainable feedstocks and enhancing production process efficiency [60].

To minimize the social and environmental negative impacts of biodiesel production and use in a country, it is important to implement sustainable and responsible production practices. This could entail working with local communities to ensure that their rights and interests are protected and taking steps to minimize the environmental impact of biodiesel production, such as using sustainable feedstocks and reducing greenhouse gas emissions. When these steps are taken, the biodiesel industry in Nigeria can contribute to a more sustainable future for the country and its populace.

11. Life cycle assessment of biodiesel production

A life cycle assessment (LCA) of biodiesel production from the four generations of feedstock involves analyzing the environmental impacts of the entire life cycle of the production process, from feedstock cultivation to biodiesel use. This includes evaluating parameters like water consumption, land use changes, energy use and greenhouse gas emissions. Comparing the LCAs of the four generations of feedstock could help to determine the most sustainable and environmentally friendly options for biodiesel production [61]. First-generation feedstocks have been associated with negative impacts on food security, deforestation and biodiversity loss. Second-generation feedstocks have lower impacts on food security but still require significant inputs of energy and chemicals during cultivation and processing. Third-generation feedstocks have the potential to reduce environmental impacts and increase yields per hectare but their cultivation and processing technologies heavily rely on water and they are still in the early stages of development [62]. Fourth-generation feedstocks aim to overcome some of the limitations of preceding generations by increasing yields, reducing inputs and minimizing land use change and other negative impacts. However, their potential environmental impacts and social implications are still uncertain and need to be carefully evaluated before widespread adoption [63,64].

12. Conclusions

This study shows that the biodiesel industry in Nigeria has potential for growth especially when there is proper support from the government and private sector. The economic viability of biodiesel must be considered in terms of production and distribution costs, as well as government subsidies and tax credits. There are technological challenges that need to be addressed, such as feedstock quality and processing. Additionally, there are social and environmental impacts to consider, including land use changes and impacts on local communities. The future of the biodiesel industry in Nigeria looks promising with potential for further research and development, technological advancements and increasing demand for sustainable fuels. Future works should concentrate on developing effective and affordable biodiesel production processes, investigating the possibilities of new feedstocks like microalgae and enhancing the sustainability of current feedstocks through improved land-use management techniques. Furthermore, incentives should be offered and a supportive environment created by policymakers and the private sector to promote the expansion of Nigeria's biodiesel industry. The focus of this study is on Nigerian biodiesel production which may limit the generalizability of the findings to other geographical areas. Also, the estimate of the economic viability of biodiesel production is based on the current market condition and might not be applicable in the future. Notwithstanding these drawbacks, this study offers insightful information about the difficulties and prospects of Nigerian biodiesel production and emphasizes the need for additional research and development in this field.

Acknowledgments

The author thanks the anonymous reviewers in particular for their suggestions to enhance the work.

Conflict of interest

The author declares no conflicts of interest.

References

1. EESI, Fossil Fuels. Environmental and Energy Study Institute, 2021. Available from: https://www.eesi.org/topics/fossil-fuels/description#:~:text=Fossil fuels—including coal%2C oil,percent of the world's energy.
2. Berhe T, Sahu O (2017) Chemically synthesized biofuels from agricultural waste: Optimization operating parameters with surface response methodology (CCD). *MethodsX* 4: 391–403. https://doi.org/10.1016/j.mex.2017.09.005
3. EIA, EIA projects nearly 50% increase in world energy use by 2050, led by growth in renewables. Energy Information Administration, 2021. Available from: https://www.eia.gov/todayinenergy/detail.php?id=49876.
4. Alsaiari M, Rozina, Ahmad M, et al. (2022) Treatment of Saussurea heteromalla for biofuel synthesis using catalytic membrane reactor. *Chemosphere* 305: 135335. https://doi.org/10.1016/j.chemosphere.2022.135335

5. Jariah NF, Hassan MA, Taufiq-yap YH, et al. (2021) Technological advancement for efficiency enhancement of biodiesel and residual glycerol refining: A mini review. *Processes* 9: 1198. https://doi.org/10.3390/pr9071198
6. Department of Transport, Renewable Fuels for Transport Policy Statement. Department of Transport, 2022. Available from: https://www.gov.ie/en/policy-information/168c6-renewable-fuels-for-transport-policy-statement/.
7. Komariah LN, Hadiah F, Aprianjaya F, et al. (2018) Biodiesel effects on fuel filter; Assessment of clogging characteristics. *J Phys Conf Ser* 1095: 012017. https://doi.org/10.1088/1742-6596/1095/1/012017
8. Ishola F, Adelekan D, Mamudu A, et al. (2020) Biodiesel production from palm olein: A sustainable bioresource for Nigeria. *Heliyon* 6: e03725. https://doi.org/10.1016/j.heliyon.2020.e03725
9. Sertoğlu K, Ugural S, Bekun FV (2017) The contribution of agricultural sector on economic growth of Nigeria. *Int J Econ Financ Issues* 7: 547–552.
10. Sokan-Adeaga AA, Ana GREE (2015) A comprehensive review of biomass resources and biofuel production in Nigeria: Potential and prospects. *Rev Environ Health* 30: 143–162. https://doi.org/10.1515/reveh-2015-0015
11. Karmakar R, Kundu K, Rajor A (2018) Fuel properties and emission characteristics of biodiesel produced from unused algae grown in India. *Pet Sci* 15: 385–395. https://doi.org/10.1007/s12182-017-0209-7
12. Da Costa J, Martins J, Lopes DQ, et al., Comparison between diesel and biodiesel produced from used cooking oil on Diesel engine performance. ResearchGate, 2018. Available from: https://www.researchgate.net/publication/329091976_Comparison_between_diesel_and_biodiesel_produced_from_used_cooking_oil_on_Diesel_engine_performance.
13. Ramírez-Verduzco LF, Rodríguez-Rodríguez JE, Jaramillo-Jacob ADR (2012) Predicting cetane number, kinematic viscosity, density and higher heating value of biodiesel from its fatty acid methyl ester composition. *Fuel* 91: 102–111. https://doi.org/10.1016/j.fuel.2011.06.070
14. Dehaghani AHS, Rahimi R (2019) An experimental study of diesel fuel cloud and pour point reduction using different additives. *Petroleum* 5: 413–416. https://doi.org/10.1016/j.petlm.2018.06.005
15. Tat ME, Van Gerpen JH (2000) Specific gravity of biodiesel and its blends with diesel fuel. *J Am Oil Chem Soc* 77: 115–119. https://doi.org/10.1007/s11746-000-0019-3
16. Oghenejoboh KM, Umukoro PO (2011) Comparative analysis of fuel characteristics of bio-diesel produced from selected oil-bearing seeds in Nigeria. *Eur J Sci Res* 58: 238–246.
17. Huang Y, Li F, Bao G, et al. (2022) Qualitative and quantitative analysis of the influence of biodiesel fatty acid methyl esters on iodine value. *Environ Sci Pollut Res* 29: 2432–2447. https://doi.org/10.1007/s11356-021-15762-w
18. Guangul FM, Sulaiman SA, Raghavan VR (2012) Elemental and thermo-chemical analysis of oil palm fronds for biomass energy conversion. *AIP Conf Proc* 1440: 1197–1205. https://doi.org/10.1063/1.4704337
19. Alleman TL, McCormick RL, Christensen ED, et al. (2016) *Biodiesel Handling and Use Guide*, 5 Ed., Golden: National Renewable Energy Laboratory. https://doi.org/10.2172/1332064
20. Gallagher KS (2013) Why & how governments support renewable energy. *Daedalus* 142: 59–77. https://doi.org/10.1162/DAED_a_00185
21. Banković-Ilić IB, Stamenković OS, Veljković VB (2012) Biodiesel production from non-edible plant oils. *Renew Sust Energ Rev* 16: 3621–3647. https://doi.org/10.1016/j.rser.2012.03.002

22. Shoen T, How to Add Lubricity, Improve Fleet Performance and Reduce Emissions. NACS, 2018. Available from: https://fuelsmarketnews.com/how-to-add-lubricity-improve-fleet-performance-and-reduce-emissions/.
23. Gouveia L, Oliveira AC, Congestri R, et al. (2017) Biodiesel from microalgae, In: Muñoz R, Gonzalez-Fernandez C, *Microalgae-Based Biofuels Bioprod From Feed Cultiv to End-Products*, Cambridge: Woodhead Publishing, 235–258. https://doi.org/10.1016/B978-0-08-101023-5.00010-8
24. Adewuyi A (2020) Challenges and prospects of renewable energy in Nigeria: A case of bioethanol and biodiesel production. *Energy Rep* 6: 77–88. https://doi.org/10.1016/j.egyr.2019.12.002
25. Anyaoku OA, Official gazette of the Nigerian bio-fuel policy and incentives. Federal Republic of Nigeria, 2007. Available from: https://www.lse.ac.uk/GranthamInstitute/wp-content/uploads/laws/1517.pdf.
26. Izah SC, Ohimain EI, Izah SC, et al. (2012) The challenge of biodiesel production from oil palm feedstock in Nigeria By feedstock in Nigeria. *Greener J Biol Sci* 3: 1–12. https://doi.org/10.15580/GJBS.2013.1.010613363
27. Canciani P, Müller B, Report on barriers to biofuels deployment. European Biofuels Technology Platform, 2015. Available from: https://www.etipbioenergy.eu/images/d3.1-barriers-to biofuels-deployment-final.pdf.
28. Bera T, Inglett KS, Wilkie AC (2020) Biofuel: Concepts and considerations. *EDIS* 2020: SL475. https://doi.org/10.32473/edis-ss688-2020
29. Aransiola EF, Daramola MO, Ojumu TV, et al. (2012) Nigerian jatropha curcas oil seeds: Prospect for biodiesel production in Nigeria. *Int J Renew Energy Res* 2: 317–325.
30. STI, Technology Needs Assessments Report for Climate Change Mitigation—Thailand. National Science Technology and Innovation Policy Office, 2012. Available from: https://tech-action.unepccc.org/wp-content/uploads/sites/2/2013/12/technologyneedsassessment-mitigation-thailand-13.pdf.
31. Christian II JA (2014) Feasibility of second and third generation biofuel in general aviation : A research report and analysis. *McNair Sch Res J* 1: 4.
32. Aro EM (2016) From first generation biofuels to advanced solar biofuels. *Ambio* 45: 24–31. https://doi.org/10.1007/s13280-015-0730-0
33. Brahma S, Nath B, Basumatary B, et al. (2022) Biodiesel production from mixed oils: A sustainable approach towards industrial biofuel production. *Chem Eng J Adv* 10: 100284. https://doi.org/10.1016/j.ceja.2022.100284
34. Wilson P, Glithero NJ, Ramsden SJ (2014) Prospects for dedicated energy crop production and attitudes towards agricultural straw use: The case of livestock farmers. *Energ Policy* 74: 101–110. https://doi.org/10.1016/j.enpol.2014.07.009
35. Siqueira SF, Francisco EC, Queiroz MI, et al. (2016) Third generation biodiesel production from microalgae phormidium autumnale. *Braz J Chem Eng* 33: 427–433. https://doi.org/10.1590/0104-6632.20160333s20150134
36. Yao Y, You Q, Duan G, et al. (2020) Quantitative trait loci analysis of seed oil content and composition of wild and cultivated soybean. *BMC Plant Biol* 20: 1–13. https://doi.org/10.1186/s12870-019-2199-7
37. Matthaus B, Özcan MM, Al Juhaimi F (2016) Some rape/canola seed oils: Fatty acid composition and tocopherols. *Z Naturforsch C J Biosci* 71: 73–77. https://doi.org/10.1515/znc-2016-0003

38. Charbonnier E, Fugeray-Scarbel A, Lemarié S (2019) Rapeseed: how to value varieties with higher nitrogen use efficiency in France. *OCL* 26: 26. https://doi.org/10.1051/ocl/2019021
39. Jambo SA, Abdulla R, Azhar SHM, et al. (2016) A review on third generation bioethanol feedstock. *Renew Sust Energ Rev* 65: 756–769. https://doi.org/10.1016/j.rser.2016.07.064
40. Mata TM, Martins AA, Caetano NS (2010) Microalgae for biodiesel production and other applications: A review. *Renew Sust Energ Rev* 14: 217–232. https://doi.org/10.1016/j.rser.2009.07.020
41. Bošnjaković M, Sinaga N (2020) The perspective of large-scale production of algae biodiesel. *Appl Sci* 10: 8181. https://doi.org/10.3390/app10228181
42. Alalwan HA, Alminshid AH, Aljaafari HAS (2019) Promising evolution of biofuel generations. Subject review. *Renew Energy Focus* 28: 127–139. https://doi.org/10.1016/j.ref.2018.12.006
43. CDP, CDP Technical Note: Biofuels. CDP, 2023. Available from: https://cdn.cdp.net/cdp-production/cms/guidance_docs/pdfs/000/003/647/original/CDP-technical-note-on-biofuels.pdf?1651855056.
44. Ogbonna I, Moheimani N, Ogbonna J (2015) Potentials of microalgae biodiesel production in Nigeria. *Niger J Biotechnol* 29: 44. https://doi.org/10.4314/njb.v29i1.7
45. Eisentraut A, Sustainable production of second-generation biofuels: Potential and perspectives in major economies and developing countries. International Energy Agency, 2010. Available from: https://www.osti.gov/etdeweb/servlets/purl/21330793.
46. Özçimen D, İnan B, An Overview of Bioethanol Production From Algae. Biofuels—Status and Perspective. InTech, 2015. Available from: https://doi.org/10.5772/59305.
47. Amir N, The cost of algae-based biofuel is still too high. Popular Science, 2022. Available from: https://www.popsci.com/energy/algae-biofuel-too-expensive/.
48. Nwozor A, Owoeye G, Olowojolu O, et al. (2021) Nigeria's quest for alternative clean energy through biofuels: An assessment. *IOP Conf Ser Earth Environ Sci* 655: 012054. https://doi.org/10.1088/1755-1315/655/1/012054
49. Igwebuike CM, Awad S, Olanrewaju YA, et al. (2021) The prospect of electricity generation from biomass in the developing countries. *Int J Smart Grid Clean Energy* 10: 150–156. https://doi.org/10.12720/sgce.10.2.150-156
50. Galadima A, Garba ZN, Ibrahim BM, et al. (2011) Biofuels production in Nigeria: The policy and public opinions. *J Sustain Dev* 4: 22. https://doi.org/10.5539/jsd.v4n4p22
51. Widenhorn S, Braving the Storm: How are Global Biofuel Policies Sustained Despite Being Contested? An Analysis of the Biofuel Discourses of the EU, Brazil and Mozambique. IBEI Working Papers, 2013. https://doi.org/10.2139/ssrn.2509888
52. Dizon LSH, Pector AA, Demafelis RB, et al. (2020) Environmental and economic viability of biodiesel production from palm oil in the Philippines. *PIChE J* 19: 35–41.
53. Hanif S, Alsaiari M, Ahmad M, et al. (2022) Membrane reactor based synthesis of biodiesel from Toona ciliata seed oil using barium oxide nano catalyst. *Chemosphere* 308: 136458. https://doi.org/10.1016/j.chemosphere.2022.136458
54. Monirul IM, Masjuki HH, Kalam MA, et al. (2015) A comprehensive review on biodiesel cold flow properties and oxidation stability along with their improvement processes. *RSC Adv* 5: 86631–86655. https://doi.org/10.1039/C5RA09555G
55. Malode SJ, Prabhu KK, Mascarenhas RJ, et al. (2021) Recent advances and viability in biofuel production. *Energy Convers Manag X* 10: 100070. https://doi.org/10.1016/j.ecmx.2020.100070

56. Mohr A, Raman S (2015) Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels, In: Gikonyo B, *Efficiency and Sustainability in Biofuel Production: Environmental and Land-Use Research*, Palm Bay: Apple Academic Press, 281–310.
57. Hassan AB, Ayodeji OV (2019) Benefits and challenges of biodiesel production in West Africa. *Niger J Technol* 38: 621. https://doi.org/10.4314/njt.v38i3.12
58. Samuel PO, Patrick SO, Bello IM (2013) Biodiesel production in Nigeria: Prospects and challenges. *Int J Mod Bot* 3: 4–9.
59. Tudge SJ, Purvis A, De Palma A (2021) The impacts of biofuel crops on local biodiversity: a global synthesis. *Biodivers Conserv* 30: 2863–2883. https://doi.org/10.1007/s10531-021-02232-5
60. Popp J, Harangi-Rákos M, Gabnai Z, et al. (2016) Biofuels and their co-products as livestock feed: Global economic and environmental implications. *Molecules* 21: 1–26. https://doi.org/10.3390/molecules21030285
61. Kiehbadroudinezhad M, Merabet A, Hosseinzadeh-Bandbafha H (2023) A life cycle assessment perspective on biodiesel production from fish wastes for green microgrids in a circular bioeconomy. *Bioresour Technol Rep* 21: 101303. https://doi.org/10.1016/j.biteb.2022.101303
62. Kiehbadroudinezhad M, Hosseinzadeh-Bandbafha H, Varjani S, et al. (2023) Marine shell-based biorefinery: A sustainable solution for aquaculture waste valorization. *Renew Energ* 206: 623–634. https://doi.org/10.1016/j.renene.2023.02.057
63. Ambaye TG, Vaccari M, Bonilla-Petriciolet A, et al. (2021) Emerging technologies for biofuel production: A critical review on recent progress, challenges and perspectives. *J Environ Manage* 290: 112627. https://doi.org/10.1016/j.jenvman.2021.112627
64. Kiehbadroudinezhad M, Merabet A, Ghenai C, et al. (2023) The role of biofuels for sustainable MicrogridsF: A path towards carbon neutrality and the green economy. *Heliyon* 9: e13407. https://doi.org/10.1016/j.heliyon.2023.e13407