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Comparative Assessment of Physico-chemical Characteristics of *Balanites aegyptiaca* (Desert Date) Biodiesel Blends and Conventional Diesel

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***Abstract**: The growing global energy demand and the environmental impact of conventional diesel impose the exploration of sustainable alternatives. This study assesses the physico-chemical properties of Balanites aegyptiaca (desert date) biodiesel blends (B20, B25, and B30) against conventional diesel (B0) and ASTM D6751 standards. Biodiesel was produced via alkali-catalyzed transesterification, achieving an 81.2% yield from seed kernels with 43.5% oil content. Important fuel properties, including density, flash point, kinematic viscosity, pour point, cloud point, and calorific value, were analyzed. The results shows that the blends have a higher density (850–860 kg/m³), elevated flash point (100–110°C), and increased viscosity (3.25–3.60 mm²/s) than diesel (830 kg/m³, 93°C, 2.60 mm²/s), with slightly lower calorific values (42.5–43.8 MJ/kg to 45.4 MJ/kg). While viscosity met ASTM D6751 limits (1.9–6.0 mm²/s), flash points were substandard (<130°C min). Cold-flow properties (pour point: -11.9 to -13.6°C; cloud point: -2 to -8°C) were inferior to diesel (-17°C; -15°C), indicating cold-climate working challenges. The B20 blend demonstrated an optimal balance between fuel properties and renewable content. Balanites aegyptiaca biodiesel is viable for diesel engines but requires additive treatment or blend optimization for cold regions. These findings support sustainable biofuel development in arid zones using non-food feedstocks.*

***Keywords:** Biodiesel, Balanites aegyptiaca, Physico-Chemical, Blends, Diesel*

1. INTRODUCTION

Global energy demand is rising at an unprecedented rate, driven by rapid population growth, industrialization, and urbanization [1, 2]. Diesel engines remain indispensable across multiple sectors due to their reliability, operational flexibility, high thermal efficiency, durability, and cost-effectiveness compared to alternative power systems [3-5]. These advantages have cemented their widespread use in transportation, power generation, agriculture, and mining operations. As industrialization and urbanization accelerate, global reliance on diesel fuel continues to intensify, with consumption expected to grow further as developing economies expand and modernize [6]. This increasing demand has driven the production of diesel-powered vehicles and industrial machinery, further consolidating diesel's critical position in global economic infrastructure [6, 7].

However, this dependence comes at substantial environmental cost: conventional diesel combustion emits noteworthy quantities of harmful chemicals, including carbon monoxide (CO), nitrogen oxides (NO_x), unburned hydrocarbons (UHC), and particulate matter (PM), contributing to environmental degradation and public health risks. These emissions worsen climate change by promoting tropospheric ozone formation, while PM accounts for nearly 20% of urban ambient air pollution worldwide [8]. Epidemiological studies have steadily linked protracted exposure to diesel emissions with increased rates of Chronic Obstructive Pulmonary Disease (COPD), cardiovascular mortality, and lung cancer [9, 10]. Accordingly, the transition toward sustainable alternatives to conventional diesel fuels has become an environmental and public health imperative.

Biodiesel, composed of mono-alkyl esters of long-chain fatty acids resulting from renewable feedstocks such as plant oils, animal fats, and algal lipids, offers a carbon-neutral alternative to petroleum diesel [11]. Feedstocks are categorized into generations based on sustainability, availability, and socio-economic impacts, with each generation addressing key limitations of its predecessors. First-generation feedstocks, derived from edible oils such as soybean, sunflower, and corn, face challenges due to their competition with food production, raising concerns over land-use change, food security, and economic scalability [12, 13]. Second-generation feedstocks utilize non-edible sources, such as waste cooking oil, and other non-food crops, thereby eradicating food-versus-fuel conflicts [14, 15].Third-generation feedstocks, primarily microalgae, offer superior sustainability characteristics, with higher oil yields per hectare than terrestrial crops [14, 16]. Fourth-generation feedstocks, employ genetically engineered microorganisms including lipid-enhanced microalgae and cyanobacteria precisely improved for targeted biofuel production [17]. Among the various potential plant-based feedstocks, numerous neglected and underutilized seeds offer significant opportunities for biodiesel development, with *Balanites aegyptiaca* (desert date) seeds representing a promising alternative.

The desert date tree (*Balanites aegyptiaca*), a drought-resistant perennial species of the Zygophyllaceae family, is indigenous to the arid and semi-arid regions of West Africa, including northern Nigeria [18]. This resilient species demonstrates exceptional environmental adaptability, flourishing under harsh climatic conditions characterized by temperature ranges of 20-30°C and minimal annual precipitation of 250-400 mm [19]. While traditionally valued for medicinal applications utilizing various plant parts including leaves, bark, and fruits, *Balanites aegyptiaca* seeds contain substantial oil content ranging from 40-87% by weight [20], with established uses in food and cosmetic industries [21]. Despite this demonstrated high oil yield potential, and favorable environmental characteristics, the species remains underutilized for biofuel applications, representing a significant untapped resource for sustainable energy development in sub-Saharan Africa [22]. This study aims to investigate the physico-chemical characteristics of *Balanites aegyptiaca* biodiesel blends as a potential substitute for conventional diesel fuel. The research findings are expected to contribute valuable data to the existing database of locally available alternative biofuel resources, thereby supporting the development of cleaner energy solutions and addressing concurrent challenges of global energy security and environmental sustainability.

2. MATERIALS AND METHODS.

2.1 Materials and Equipment

The study utilized desert date (*Balanites aegyptiaca*) seeds, diesel fuel, and various chemicals and reagents, including methanol (CH_3OH), potassium hydroxide (KOH), distilled water (H_2O), and *n*-hexane, all of analytical grade. Key equipment and instruments used included a laboratory heating source**,** oven, viscometer, cleveland open-cup flash point tester, bomb calorimeter, stopwatch, digital balance, measuring cylinder, magnetic stirrer, beakers, retort stand, conical flasks, separating funnels, thermometer, and density bottle.

2.2 Methods

2.2.1 Sample Collection and Preparation

Desert date fruits (Balanites aegyptiaca) were procured from local markets in Mubi metropolis, Adamawa State, Nigeria, during the peak harvesting period of November-January. The fruits were visually inspected, and only mature fruits were selected for the study, while immature or damaged fruits were excluded. The selected fruits were soaked in clean water to facilitate removal of the seed coats, followed by thorough washing to eliminate pulp material. The cleaned seeds were sun-dried, and the dried seeds were manually cracked using a manual kernel cracker to extract the kernels, which were further air-dried to minimize moisture content. The kernels were subsequently ground to fine powder using a mortar and pestle to enhance surface area for oil extraction. This preparation method was adapted from Usman, et al. [19].

2.2.2 Oil extraction process

Oil was extracted from the prepared desert date kernels in the Chemical Science Laboratory of Federal Polytechnic Mubi, Adamawa State, Nigeria, using a Soxhlet apparatus with n-hexane as solvent. Ground kernel samples (100 g) were placed in a thimble and extracted with 200 mL n-hexane at 70°C for 4 hours. The oil-hexane mixture was separated by distillation to obtain crude oil. The extraction was repeated until sufficient oil was obtained for analysis. This method was adapted from Alemayehu [23]. Oil yield was calculated using Equation 1:

$$\%\ Oil\ Yield = \frac{Weight\ of\ Oil\ Extracted\ (g)}{Weight\ of\ Seed\ used\ (g)} * 100 \tag{1}$$

2.2.3 Biodiesel Production

A single-step alkali-catalyzed transesterification process was used for biodiesel production from the extracted *Balanites aegyptiaca* oil. The process involved heating 146 g of the extracted oil to 60°C, while simultaneously preparing the catalyst solution by dissolving 1 g KOH in 45 g methanol to form potassium methoxide. The methoxide solution was added to the heated oil at a 6:1 molar ratio (methanol: oil) and stirred at 500 rpm for 20 minutes. The reaction mixture was transferred to a separating funnel and allowed to settle for 24 hours, forming two distinct phases: biodiesel (upper layer) and glycerol (lower layer). After separating the glycerol, the biodiesel was purified by washing with warm distilled water to remove residual impurities, followed by oven drying. This method was adapted from Kaisan [24]. The process was repeated to obtain sufficient biodiesel for blending with petroleum diesel at various ratios. Biodiesel yield was calculated using Equation 2:

$$Process\ Yield\ (\%) = \frac{Clean\ Biodiesel\ (g)}{Oil\ used\ (g)} * 100 \tag{2}$$

2.2.4 Biodiesel Blending

Four test fuels were prepared, including neat petroleum diesel (B0) and three biodiesel-diesel blends: B20 (20% biodiesel, 80% diesel), B25 (25% biodiesel, 75% diesel), and B30 (30% biodiesel, 70% diesel). The blends were prepared by volumetrically mixing *Balanites aegyptiaca* biodiesel with petroleum diesel. Blends were homogenized using a magnetic stirrer at room temperature and stored in airtight containers to prevent degradation. All preparations were conducted under laboratory conditions.

2.2.5 Determination of Physico-Chemical Properties of the Test Fuels

The physico-chemical properties of the test fuels were assessed through standardized testing protocols following ASTM D6751 specifications. This assessment was conducted to evaluate and compare the fundamental characteristics of *Balanites aegyptiaca* biodiesel blends against conventional diesel fuel. The evaluation aimed to determine how well the *Balanites aegyptiaca* biodiesel blends meet established fuel quality standards and specifications. The physico-chemical parameters assessed included density, flash point, kinematic viscosity, pour point, cloud point, and calorific value.

2.2.6 Determination of Density

The density of the fuel samples was determined using the density bottle method. The measurements were conducted at a constant temperature of 15°C, in accordance with the ASTM D792 test procedure. Initially, the mass of an empty density bottle (W1) was measured, followed by the mass of the same bottle filled with distilled water (W2). Subsequently, the mass of another empty density bottle (W3) and the mass of the bottle filled with the fuel sample (W4) were measured and recorded. The density (ρ) of the fuel samples was calculated using Equation 3

$$Density\ (\rho) = \frac{W4 - W3}{W2 - W1} \tag{3}$$

Where:
ρ = Density of the fuel sample (kg/m³)
W1 = Mass of the empty density bottle (kg)
W2 = Mass of the density bottle filled with distilled water (kg)
W3 = Mass of the second empty density bottle (kg)
W4 = Mass of the density bottle filled with the fuel sample (kg)

2.2.7 Determination of Flash Point

Flash point measurements were conducted using the Cleveland Open Cup method following ASTM D92 standard procedures. Each fuel sample was placed in a clean test cup filled to the designated mark and positioned within the heating apparatus. A calibrated thermometer was inserted into the sample without contact with the cup bottom. Samples were heated at a controlled rate of 5-6°C/min. Test flame application commenced when the sample temperature reached approximately 28°C below the anticipated flash point, with subsequent flame tests conducted at 2°C intervals. The flash point was defined as the lowest temperature at which the test flame produced a distinct flash propagating across the entire fuel surface. All measurements were conducted in triplicate to ensure reproducibility, and mean values were reported.

2.2.8 Determination of Kinematic Viscosity

Kinematic viscosity was determined following ASTM D445 using a calibrated Ostwald viscometer. Fuel samples (20 mL) were heated to 40°C for 30 minutes in a viscometer bath. Flow time between two marked points in the capillary tube was recorded, and kinematic viscosity (ν) was calculated using Equation 4:

$$V = kt \tag{4}$$

Where:
V = viscosity (mm^2/s)
k = the constant calibration of the viscosity (mm^2/s^2)
t = time (s)

2.2.9 Determination of Pour Point

The pour point of fuel samples was determined following ASTM D97 standard methodology. Test sample (5 mL) was transferred into standard test tube and secured in wooden clamp equipped with calibrated thermometers. The sample were cooled below 0°C by placement in a beaker containing ice until solidification occurred. Subsequently, the test tube was removed from the cooling medium, tilted on the clamp, and observed at regular intervals while monitoring the sample's flow characteristics. The lowest temperature at which the fuel was observed to flow was recorded as its pour point. The procedure was repeated for each fuel sample, with all measurements conducted in triplicate to ensure reproducibility.

2.2.10 Determination of Cloud Point

The cloud point of the fuel sample was determined following ASTM D2500 standard procedure. A test sample (5 mL) was transferred into a standard test tube and placed in a beaker containing crushed ice for cooling. The sample was observed continuously during the cooling process until the first appearance of wax crystals on the surface was detected. The temperature corresponding to this initial crystallization was recorded as the cloud point. The measurement was conducted in triplicate.

2.2.11 Determination of Calorific Value

The calorific value of the fuel sample was determined using a CAL2K ECO bomb calorimeter following ASTM D975, standard procedure. The calorimeter was calibrated using benzoic acid as a reference standard to establish the heat capacity of the system. Approximately 1 g of the fuel sample was accurately weighed and transferred into the combustion chamber, which was then pressurized with pure oxygen. Upon ignition, the heat released was measured based on the temperature rise of the surrounding water bath, and the calorific value was calculated from the observed temperature change.

3. RESULT AND DISCUSSION.

3.1 Oil Yield and Biodiesel Production Efficiency

The oil yield from *Balanites aegyptiaca* seed kernels was 43.5%, aligning with previous studies yields between 30% and 49% [1, 18, 22] and the 30–50% range regardless of the extraction method used reported by Chapagain and Wiesman [25]. The yield meets the commercial viability threshold of 30–55% for biodiesel feedstocks [26], confirming *Balanites aegyptiaca* potential for large-scale biodiesel production. The transesterification process achieved an 81.2%, biodiesel yield with 15.9% glycerol yield and 2.9% process losses. The high conversion efficiency demonstrates the effectiveness of alkali-catalyzed transesterification, aligning with previous studies [19, 21, 27, 28]. This efficiency demonstrates the technical feasibility of utilizing *Balanites aegyptiaca* as a biodiesel feedstock, particularly in arid regions where it thrives without competing with food crops.

3.2 Comparative Analysis of Fuel Properties

Table 1 presents the physico-chemical properties of conventional diesel (B0) and *Balanites aegyptiaca* biodiesel blends (B20, B25, and B30), benchmarked against ASTM D6751 standards

Table 1: Experimental properties of conventional diesel and biodiesel blends vs international standards

Property	Unit	B0	B20	B25	B30	ASTM D6751
Density	kg/m^3	830 ±1.2	850±1.5	855±1.3	860±1.4	880
Flash Point	^{0}C	93±0.8	100±1.0	106±1.2	110±1.5	130 (min)
Kinematic Viscosity	mm^2/s	2.6±0.05	3.25±0.08	3.39±0.09	3.60±0.10	1.9 –6.0
Pour Point	^{0}C	-17±0.5	-13.6±0.4	-12.8±0.3	-11.9±0.3	-15 to -16
Cloud Point	^{0}C	- 15±0.3	- 8±0.4	-5±0.3	-2±0.2	-3 to -12
Calorific Value	MJ/kg	45.4±0.3	43.8±0.4	43.2±0.3	42.5±0.4	-

Values are presented as mean ± standard deviation (n=3)

3.2.1 Density Analysis

Fuel density plays a critical role in injection characteristics, combustion efficiency, and volumetric energy content [29]. As shown in Table 1, the experimental results demonstrate a linear increase in density with increasing biodiesel concentration, ranging from 830 kg/m³ (B0) to 860 kg/m³ (B30). The B20 and B25 blends exhibited intermediate densities of 850 kg/m³ and 855 kg/m³, respectively. This trend is consistent with findings from previous research [30]. The observed increase can be attributed to the higher molecular weight of biodiesel's triglyceride molecules relative to conventional diesel hydrocarbons [31]. From a regulatory compliance perspective, the blends satisfy the ASTM D6751 standard for practical applications. However, higher fuel density increases flow resistance, potentially leading to inefficient fuel injection performance. Conversely, lower density fuels enhance atomization efficiency and promote better fuel-air mixture formation, resulting in improved combustion characteristics [29].

3.2.2 Flash Point Analysis

The flash point characteristics of *Balanites aegyptiaca* biodiesel blends (B20, B25, and B30) and petroleum diesel (B0) were investigated to evaluate their safety characteristics. The results in Table 1, demonstrate a positive trend between biodiesel content and flash point increase. The flash points were 93°C for B0, 100°C for B20, 106°C for B25, and 110°C for B30. This increase can be attributed to biodiesel's higher molecular weight compounds and saturated fatty acid ester composition, which reduce volatility [32-34]. Although the biodiesel blends did not meet the ASTM D6751 standard's minimum flash point limit of 130°C, they exhibited significantly higher flash points than petroleum diesel, indicating improved safety during handling and storage due to reduced ignition risk. The findings highlight the safety benefits of *Balanites aegyptiaca* biodiesel blends as potentially safer alternatives to conventional diesel fuel.

3.2.3 Kinematic Viscosity Analysis

The kinematic viscosity of (B0) and *Balanites aegyptiaca* biodiesel blends (B20, B25, and B30) was measured at 40°C according to ASTM D445. The results in Table 1, show a direct relationship between biodiesel concentration and kinematic viscosity, with values increasing from 3.25 mm²/s for B20 to 3.60 mm²/s for B30, compared to 2.60 mm²/s for petroleum diesel (B0). All tested fuels remained within the ASTM D6751 specified range of 1.9–6.0 mm²/s, ensuring optimal engine performance and fuel system compatibility. The increase in viscosity is attributed to the larger molecular structures and complex intermolecular interactions of fatty acid methyl esters [34-36]. The findings confirm that *Balanites aegyptiaca* biodiesel blends exhibit suitable viscosity characteristics for use in conventional diesel engines, supporting their viability as alternative fuels.

3.2.4 Pour point analysis

Pour point represents a critical cold-flow property that defines the minimum temperature at which fuel maintains fluidity, directly affecting operational performance in low-temperature environments [37]. The pour point of *Balanites* *aegyptiaca* biodiesel blends (B20, B25, and B30) was evaluated to assess their low-temperature operability. The results in Table 1 shows that the pour point increased progressively with biodiesel concentration, from -17°C for pure diesel (B0) to -13.6°C (B20), -12.8°C (B25), and -11.9°C (B30). These values exceed the ASTM D6751 specification range of -15°C to -16°C for biodiesel. The observed increase in pour point is attributed to biodiesel's higher saturation level and longer carbon chain length compared to petroleum diesel [38]. For cold-climate applications, cold-flow improver additives or alternative blending strategies may be necessary to enhance low-temperature performance characteristics [34].

3.2.5 Cloud point analysis

Cloud point represents a critical cold-flow parameter that significantly influences fuel performance under low-temperature conditions, defined as the temperature at which paraffin wax crystals begin to precipitate, potentially causing fuel filter blockage and compromising engine operability [6]. The cloud point characteristics of *Balanites aegyptiaca* biodiesel blends were systematically evaluated to assess their cold-weather performance suitability. As presented in Table 1, the cloud point values increased progressively with biodiesel concentration: neat diesel (B0) exhibited a cloud point of -15°C, while the biodiesel blends showed significantly elevated values of -8°C (B20), -5°C (B25), and -2°C (B30). This increase in cloud point is attributed to the higher degree of saturation in fatty acid methyl esters (FAMEs) present in biodiesel, which promotes crystallization at elevated temperatures compared to petroleum diesel. The observed trend aligns with established literature demonstrating a positive correlation between biodiesel blend ratio and cloud point temperature. Continuous monitoring of cold-flow properties remains essential for ensuring reliable fuel system performance in cold-climate applications. The results suggest that higher blend ratios may require operational considerations or fuel conditioning strategies in regions experiencing severe winter conditions.

3.2.6 Calorific value analysis

The calorific value is a critical thermodynamic property that directly affects fuel energy density and combustion efficiency, serving as a key parameter for evaluating fuel performance [38]. This study determined the calorific values of petroleum diesel (B0) and *Balanites aegyptiaca* biodiesel blends (B20, B25, and B30) to assess their energy content and potential impact on engine performance. The results in Table 1 shows an inverse relationship between biodiesel concentration and calorific value. Petroleum diesel (B0) had the highest calorific value of 45.4 MJ/kg, while biodiesel blends showed decreasing values of 43.8 MJ/kg (B20), 43.2 MJ/kg (B25), and 42.5 MJ/kg (B30), representing energy reductions of 3.5%, 4.8%, and 6.4%, respectively. The decrease in calorific values is attributed to the higher oxygen content in fatty acid methyl esters (FAMEs), which reduces the carbon-to-hydrogen ratio and lowers the heating value [30, 32-34].

4. CONCLUSION

This comprehensive investigation demonstrates the technical viability of *Balanites aegyptiaca* as a sustainable biodiesel feedstock. The oil yield of 43.5% and efficient transesterification process (81.2%) confirm the technical feasibility of large-scale production. This study has certain limitations that should be acknowledged. The investigation was limited to physico-chemical characterization and did not include engine performance testing or exhaust emission analysis, which are essential for a comprehensive fuel assessment. Furthermore, oxidative stability testing was not conducted, despite its importance for long-term storage. While economic feasibility was briefly discussed, a more detailed techno-economic assessment is needed to confirm large-scale production viability. These aspects represent important directions for future research. Despite these limitations, the B20 blend emerges as the most balanced and promising formulation, maintaining critical properties within acceptable ranges while providing 20% renewable content. Specifically, B20 exhibited the smallest deviation from ASTM standards, with a flash point closest to the minimum threshold, cold-flow properties superior to higher blends, and only a 3.5% reduction in calorific value, making it the most viable option for immediate implementation. The feedstock's suitability for arid and semi-arid regions, coupled with its non-food competing nature, positions it as a promising alternative fuel.

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REFERENCES

[1] Ahmed, A., Ali, A., Mubashir, M., Lim, H. R., Khoo, K. S., & Show, P. L. (2023). Process optimization and simulation of biodiesel synthesis from waste cooking oil through supercritical transesterification reaction without catalyst. *Physics: Energy*, *5*(2), 1-12, https://doi.org/10.1088/2515-7655/acb6b3.

[2] Bousbaa, H., Kaid, N., Alqahtani, S., Maatki, C., Naima, K., Menni, Y., & Kolsi, L. (2024). Prediction and Simulation of Biodiesel Combustion in Diesel Engines: Evaluating Physicochemical Properties, Performance, and Emissions. *Fire*, *7(10)*, *364-387*, https://doi.org/10.3390/fire7100364.

[3] Ahmed, B. M., Luo, M., Elbadawi, H. A. M., Mahmoud, N. M., & Sui, P. C. (2025). Experimental Study of 2-Ethylhexyl Nitrate Effects on Engine Performance and Exhaust Emissions of Diesel Engine Fueled with Diesel–2-Methylfuran Blends. *Energies*, *18*(1) 98-114. https://doi.org/https://doi.org/10.3390/en18010098.

[4] Mishra, P., Mohapatra, T., Sahoo, S. S., Padhi, B. N., Giri, N. C., Emara, A., & AboRas, K. M. (2024). Experimental assessment and optimization of the performance of a biodiesel engine using response surface methodology. *Energy, Sustainability and Society*, *14*(28) 1-22. https://doi.org/10.1186/s13705-024-00447-2.

[5] Rahman, S. M. A., Fattah, I. M. R., Ong, H. C., & Zamri, M. F. M. A. (2021). State-of-the-Art of Strategies to Reduce Exhaust Emissions from Diesel Engine Vehicles. *Energies*, *14*(6), 1766-190. https://doi.org/https://doi.org/10.3390/en14061766.

[6] Nguyen, V. G., Pham, M. T., Le, N. V. L., Le, H. C., Truong, T. H., & Cao, D. N. (2023). A comprehensivereview on the use of biodiesel for diesel engines. *International Journal of Renewable Energy Development*, *12*(4), 720-740. https://doi.org/10.14710/ijred.2023.54612.

[7] Pham, M. T., Pham, V. T., & Cao, D. N. (2023). Design and fabrication of heating device for vegetable oil used for diesel engine. *Journal of Technology & Innovation (JTIN)*, *3*(1), 29-37. https://doi.org/10.26480/jtin.01.2023.29.37.

[8] World Health Organization. (2015). *Regional Office for Europe(OECD) Economic cost of the health impact of air pollution in Europe: clean air, health and wealth*. WHO Regional Office Publication, Copenhagen, Denmark.

[9] Uzoma, N., & Ojapah, M. M. (2023). Experimental Analysis of Gaseous Emission in 2-Stroke Single Cylinder Engine Using Ethanol Gasoline Blends. *International Journal of Research and Innovation in Applied Science (IJRIAS)*, *VIII*(IV), 123-136. https://doi.org/10.51584/IJRIAS.

[10] Chaurasiya, P. K., Singh, S. K., Dwivedi, R., & Choudri, R. V. (2019). Combustion and emission characteristics of diesel fuel blended with raw jatropha, soybean and waste cooking oils. *Heliyon*, *5*(5), 1-7. https://doi.org/10.1016/j.heliyon.2019.e01564.

[11] Pasha, M. K., Dai, L., Liu, D., Guo, M., & Du, W. (2021). An overview to process design, simulation and sustainability evaluation of biodiesel production. *Biotechnology for Biofuels*, *14*(129), 1-23. https://doi.org/10.1186/s13068-021-01977-z.

[12] Alalwan, H. A., Alminshid, A. H., & Aljaafari, H. A. S. (2019). Promising Evolution of Biofuel Generations. Subject Review. *Renewable Energy Focus*, *28*, 127-139. https://doi.org/10.1016/j.ref.2018.12.006.

[13] Eluwa, S. E., & Kilanko, O. (2024). Biofuel as an alternative for Sub-Saharan Africa's transition to cleaner energy. *Academia Green Energy,(1), 1-9*. https://doi.org/10.20935/AcadEnergy6227.

[14] Ibrahim, H. (2019). Biodiesel Production: Feedstocks, Usage, and Global Status- A Review. *Nigerian Research Journal of Chemical Sciences*, *7*, 38-49.

[15] Kamil, M., Ramadan, K., Ghenai, C., Olabi, A. G., & Nazzal, I. T. (2019). Emissions from Combustion of Second-Generation Biodiesel Produced from Seeds of Date Palm Fruit (Phoenix dactylifera L.). *Applied Sciences*, *9*(18), 3720-3744. https://doi.org/10.3390/app9183720.

[16] Chakraborty, S., & Dunford, N. T. (2024). Algae: Nature's Renewable Resource for Fuels and Chemicals. *Biomass*, *4*, 329–348. https://doi.org/10.3390/biomass4020016.

[17] Tiwari, C., Verma, T. N., Dwivedi, G., & Verma, P. (2023). Energy-Exergy Analysis of Diesel Engine Fueled with Microalgae Biodiesel-Diesel Blend. *Applied Sciences*, *13(3),* 1857-1880. https://doi.org/10.3390/app13031857

[18] Aboje, A. A., Ohile, S. O., Uthman, H., Olutoye, M. O., & Nwachukwu, C. A. (2023). Optimization and Characterization of Biodiesel Production from Desert Date Seed Oil (Balanites aegyptiaca) via Transesterification Reaction. *Journal of Energy Technology and Environment*, *5*(2), 181-186. https://doi.org/10.5281/zenodo.8025638

[19] Usman, M., Ibrahim, H., & Agbaji, E. (2022). Extraction, Characterization and Determination of Physicochemical Properties of Biodiesel obtained from Desert Date (Balanites aegyptiaca) seed oil. *Journal of Applied Science and Environmental Management*, *26*(12), 2045-2051. https://doi.org/10.4314/jasem.v26i12.19.

[20] Obidah, W., Nadro, M. S., Tiyafo, G. O., & Wurochekke, A. U. (2009). Toxicity of Crude Balanites aegyptiaca Seed Oil in Rats. *Journal of American Science*, *5*(6), 13-16.

[21] Usman, A., & Rufai, I. A. (2020). Properties of Balanites Aegyptiaca Biodiesel as a Pottential Energy Carrier in the Drylands of Nigeria. *International Journal of Energy Engineering*, *10*(4), 95-101. https://doi.org/10.5923/j.ijee.20201004.01.

[22] Dass, P. M., Louis, H., Alheri, A., Amos, P. I., Bifam, M., & Ago, M. A. (2018). Production of Biodiesel Oil from Desert Dates (Balanites aegyptiaca) Seeds Oil Using a Hetrogeneous Catalyst Produced from Mahogany (Khaya senegalensis) Fruit Shells. *Analytical Chemistry: An Indian Journal*, *18*(1).

[23] Alemayehu, H. G. (2015). Physico-chemical characterization and extraction of oil from balanites aegyptiaca plant (seed). *World Journal of Pharmaceutical Research*, *4*(11), 1723-1732.

[24] Kaisan, M. U. (2017). *Modelling and Simulation of Biodiesel Blends Performance in Compression Ignition Engines* PhD thesis, Mechanical Engineering. Ahmadu Bello University, Zaria, Nigeria.

[25] Chapagain, B., & Wiesman, Z. (2005). Larvicidal effects of aqueous extracts of Balanites aegyptiaca (desert date) against the larvae of Culex pipiens mosquitoes. *African Journal of Biotechnology*, *4*(11), 1351-1354.

[26] Ndana, M., Garba, B., Hassan, L. G., & Faruk, U. Z. (2011). Evaluation Of Physicochemical Properties Of Biodiesel Produced From Some Vegetable Oils Of Nigeria Origin. *Bayero Journal of Pure and Applied Sciences*, *4*(1), 67-71. https://doi.org/10.4314/bajopas.v4i1.15.

[27] Oluwaniyi, O. O., Oloruntele, I. O., Olaniyi, O. B., Hauwa, Sekoni, A., & Hamza, M. I. (2023). Productionand Characterization of Biodiesel from Prunus amygdalus “dulcis” Seed Oil. . *International Journal of Scientific Research in Chemical Sciences*, *10*(4), 24-31.

[28] Oni-Adimabua, O. N., Ifeanyi-Nze, F. O., Abimbolu, A. K., Opadokun, E. O., Omolusi, A. R., Ezeokolie, E. D., Udoh, E. A., Afuape, A. R., Areola, M. O., Wokoma, P.-T. B., Odoh, E. C., Aiso, S. U., Francis, C. J., Egbo, J. O., Ayanleke, T. A., & Ankomah, N. O. (2024). Production, optimization, and characterization of biodiesel from almond seed oil using a bifunctional catalyst derived from waste animal bones and almond shell. *European Journal of Sustainable Development Research*, *8*(3), 1-10.

[29] Hoang, A. T. (2021). Prediction of the density and viscosity of biodiesel and the influence of biodiesel properties on a diesel engine fuel supply system. *Journal of Marine Engineering and Technology 20*(5), 299-311. https://doi.org/10.1080/20464177.2018.1532734.

[30] Khan, M. B., Kazim, A. H., Shabbir, A., Farooq, M., Farooq, H., Ali, Q., Danish, M. R., Qureshi, N. S., & Rab, H. A. (2020). Performance and emission analysis of high purity biodiesel blends in diesel engine. *Advances in Mechanical Engineering*, *12*(11), 1–10. https://doi.org/https://doi.org/10.1177/1687814020974156.

[31] Knothe, G., Gerpen, J. V., & Krahl, J. (2005). *The Biodiesel Handbook*. AOCS Press.

[32] Chavan, M., Amarnath, H. K., & Hebbal, O. D. (2014). Experimental Investigation on Performance, Emission and Combustion Characteristics of Single Cylinder Diesel Engine Running on Desert Date (Balanites Aegyptiaca) Biodiesel. *International Journal of Engineering Research & Technology (IJERT)*, *3*(8), 1352-1358.

[33] Naik, N. S., & Balakrishna, B. (2016). Experimental evaluation of a diesel engine fueled with Balanites aegyptiaca (L.) Del biodiesel blends. *Biofuels.* https://doi.org/https://doi.org/10.1080/17597269.2016.1168026.

[34] Ravi, S. D., Harlapur, M. D., & Pneeth, P. R. (2020). Experiment With a Diesel Engine Fuelled by Biodiesel Mixes with Balanites Aegyptiaca (L.). *International Journal of Research in Mechanical, Mechatronics and Automobile Engineering(IJRMMAE)*, *6*(1), 36-44.

[35] Odega, C., Anguruwa, G., & Fakorede, C. (2021). Biodiesel Production and Characterization from Used Vegetable Oil. *Jounal of Applied Science Environmental Management*, *25*(4). 537-542 https://doi.org/https://doi.org/10.4314/jasem.v25i4.7.

[36] Saleh, F. A., Allawi, M. K., S.Imran, M., & Samarmad, A. O. (2024). A Simulation of the Impact of Biodiesel Blends on Performance Parameters in Compression Ignition Engine. *Journal of Ecological Engineering*, *25*(7), 1-7.

[37] Alptekin, E., & Canakci, M. (2011). Optimization of transesterification for methyl ester production from chicken fat. *Fuel*, *90*(8), 2630-2638. https://doi.org/10.1016/j.fuel.2011.03.042.

[38] Ozcanli, M., Gungor, C., & Aydin, K. (2013). Biodiesel Fuel Specifications: A Review. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *35*(7), 635-647. https://doi.org/10.1080/15567036.2010.503229.