

NOVEL SOLVENTLESS GREEN SYNTHESIS OF BIODIESEL VIA ACID CATALYZED TRANSESTERIFICATION OF PALM KERNEL OIL WITH CELLOBIOSE

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Abstract

The persistent combustion of fossil fuels has intensified greenhouse gas emissions and accelerated global warming, driving an urgent search for renewable and ecologically benign energy alternatives. This study reports a novel solventless green synthesis of biodiesel through the acid catalyzed transesterification of palm kernel oil (PKO) with laboratory synthesized cellobiose, thereby eliminating the conventional reliance on toxic methanol or ethanol. Cellobiose (0.6 g) was dissolved in 1 mL of concentrated hydrochloric acid and reacted with 100 mL of freshly dewaxed PKO under reflux at 115 °C for 6 hours at 800 rpm. The synthesized cellobiose was authenticated using matrix assisted laser desorption ionization time of flight mass spectrometry (MALDI TOF MS), which revealed potassium adduct peaks at m/z 379.17 $[Mw-2H+K]^+$, 380.18 $[Mw-H+K]^+$, and 381.19 $[Mw+K]^+$, confirming the presence of a disaccharide with two glucose units joined by a $\beta(1\rightarrow4)$ glycosidic linkage. Fourier transform infrared (FT IR) spectroscopy of the biodiesel product showed diagnostic absorption bands at 1465 and 1163 cm^{-1} , verifying successful conversion from PKO to fatty acid alkyl esters. Gas chromatography mass spectrometry (GC MS) analysis revealed that the biodiesel mixture consists predominantly of fatty acid ethyl esters (57.38%) and fatty acid methyl esters (22.17%), giving an overall yield of 96.75%. The physicochemical characterization returned a flash point of 144 °C, a pour point of -11 °C, and a kinematic viscosity of 2.02 mm^2/s , all within established biodiesel quality standards. These findings demonstrate that cellobiose can serve as a viable and green transesterification agent for the production of high quality biodiesel without the use of conventional organic solvents.

Keywords: Biodiesel synthesis; Cellobiose; Solvent free production; Green chemistry; Palm kernel oil; Acid catalyzed transesterification; Fatty acid alkyl esters

1. Introduction

The combustion of fossil fuels remains the single largest contributor to anthropogenic greenhouse gas emissions, with carbon dioxide concentrations in the atmosphere having surpassed 420 ppm as of 2024 (Solaymani, 2023). The resulting acceleration of global warming, coupled with the depletion of finite petroleum reserves, has compelled researchers and policymakers to explore renewable energy alternatives capable of powering transportation and industrial sectors without the attendant environmental degradation (Khan and Sudhakar, 2021). Among these alternatives, biodiesel has emerged as one of the most promising liquid biofuels, owing to its compatibility with existing diesel engines, its biodegradability, and its capacity to reduce particulate emissions and sulfur content in exhaust gases (Araby and Araby, 2024).

The conventional production of biodiesel relies on the transesterification of vegetable oils or animal fats with short chain alcohols, most commonly methanol, in the presence of a base or acid catalyst (Selaimia *et al.*, 2015). While this approach has been widely adopted at both laboratory and industrial scales, it carries several inherent limitations. Methanol is a volatile and acutely toxic substance that poses occupational health risks and environmental hazards throughout its lifecycle (Aly, 2019). Furthermore, the cost of feedstock oils, which can account for 70% to 95% of the total production cost, imposes a significant economic burden on commercial biodiesel operations (Balat, 2011). The requirement for inexpensive and readily available catalysts has also been identified as a critical bottleneck in the quest for economically viable biodiesel production (Yaghi *et al.*, 2025; Yadav and Yadav, 2023).

Second generation biofuels, derived from non edible cellulosic biomass, have attracted considerable attention as a means of circumventing the food versus fuel debate that has dogged first generation biofuels (Chen *et al.*, 2017; Khanna *et al.*, 2011). Biopolymers such as cellulose, hemicellulose, and lignocellulose are the most abundant organic compounds on Earth and represent a virtually inexhaustible supply of carbon for fuel production (Aboelazayem *et al.*, 2022; Asif *et al.*, 2025; Wo *et al.*, 2025). The complexity of lignocellulosic biomass, however, necessitates its conversion into simpler intermediates before it can be used as a reactant in biodiesel synthesis (Siakpebru and Morais, 2026; Vojtov and Leinweber, 2024; Liu and Yu, 2022). Pretreatment methods, including microbiological, physical, and chemical approaches, have been developed to break down the recalcitrant structure of lignocellulose into fermentable sugars and other processable fractions (Abubakar, 2019; Esi *et al.*, 2020; Meenakshisundaram *et al.*, 2022; Chen *et al.*, 2024).

Despite these advances, the absence of an economically feasible and industrially scalable technology for converting lignocellulosic biomass directly into biodiesel continues to limit its widespread adoption (Chintagunta *et al.*, 2021; Ntunka *et al.*, 2025). Oleaginous yeasts and certain microalgae have been explored as alternative biodiesel feedstocks because of their ability to accumulate lipids up to 75% of their dry body mass when fed on glucose and xylose (Sanchez Solis *et al.*, 2024; Dias *et al.*, 2023; Patel *et al.*, 2020). Nevertheless, economic assessments of lipid fermentation for fuel production have raised questions about its commercial viability under current technological conditions. Integrated biorefinery approaches that generate high value co products alongside fuel may improve the economics of these processes (Ratledge and Wynn, 2002).

A paradigmatic shift from solvent based to solvent free biodiesel synthesis would address many of the shortcomings outlined above. The use of active cellulosic intermediates, such as cellobiose, as the transesterification agent in place of methanol or ethanol has not been reported in the literature prior to this work. Cellobiose, a disaccharide consisting of two glucose units linked by a $\beta(1\rightarrow4)$ glycosidic bond, can be obtained from the hydrolysis of cellulose and possesses hydroxyl groups that are theoretically capable of participating in transesterification reactions (Donnelly and Baumann, 2022; Zhou *et al.*, 2024). The present study investigates the feasibility of this novel approach by conducting acid catalyzed transesterification of palm kernel oil with synthetic cellobiose under reflux conditions, eliminating the need for methanol or ethanol entirely. The resulting biodiesel product was characterized using MALDI TOF MS, FT IR spectroscopy, and GC MS, and its physicochemical properties were evaluated against established ASTM standards.

2. Materials and Method

All reagents employed in this study were of analytical grade and were used without further purification unless otherwise stated. Hydrochloric acid (HCl, concentrated), absolute ethanol, sodium hydroxide (NaOH), carbon tetrachloride (CCl_4), glacial acetic acid, potassium iodide solution (10%), iodine trichloride, 0.1 N sodium thiosulphate solution, starch indicator, chloroform, Wij's solution (iodine monochloride), phenolphthalein (Merck, Germany), and n hexane (99% purity, Merck, Germany) were procured from commercial suppliers. The cellobiose was synthesized in the laboratory at the Department of Chemistry, University of Ilorin, while the palm kernel oil was sourced from a local market in Ilorin, Kwara State, Nigeria.

2.1 Equipment and Apparatus

The equipment utilized included a Corning 6795 420D stirring hot plate, an electronic digital weighing balance (Ohaus Adventurer, model AR 3130), a thermo regulator heater with stirrer (Heizung chauffage, MGW LAUDA, D6970, Germany), Pyrex separating funnels, Pyrex round bottom flasks, a mercury in glass thermometer, an ATC refractometer, a semi automatic Cleveland flash point tester, a thermostatic water bath (Model No. 6801TI, Medica Inst. Mgt Coy, India), a digital pH meter (Exstick, India), a MALDI Biotyper (Bruker Daltonics, Pune, India), and a GC MS QP2010SE (Shimadzu, Japan).

2.2 Transesterification Reaction

A mass of 0.6 g of the synthesized cellobiose was dissolved in 1 mL of concentrated HCl, which served as both solvent for the sugar and acid catalyst for the reaction. This solution was added to 100 mL of freshly dewaxed palm kernel oil contained in a 250 mL round bottom flask. The mixture was refluxed at 115 °C for 6 hours at a stirring speed of 800 rpm. Following the reaction, the contents were filtered and transferred into a separating funnel. The product underwent a fourfold purification using boiling distilled water to remove residual acid, glycerol, and other side products. The purified mixture was then allowed to separate under gravity on a steam bath for 48 hours. Two distinct layers were obtained: an upper layer consisting of biodiesel and a lower glycerol rich layer (Fernando *et al.*, 2007). The biodiesel yield was calculated as the percentage mass ratio of biodiesel obtained to the initial mass of PKO used.

3. Results and Discussion

3.1 MALDI TOF MS Analysis of Cellobiose

Matrix assisted laser desorption ionization time of flight mass spectrometry (MALDI TOF MS) was employed to verify the identity and purity of the synthesized cellobiose. The analysis was performed using α cyano 4 hydroxycinnamic acid (CHCA) as the matrix. A 1 mg sample was dissolved in 1 mL of methanol, thoroughly mixed with the CHCA matrix solution, spotted onto a MALDI plate, and allowed to desiccate at ambient temperature for several minutes prior to analysis (Lee *et al.*, 2020).

The resulting mass spectrum, presented in Figure 2, reveals three prominent peaks at m/z values of 379.17, 380.18, and 381.19. These signals correspond to potassium adducts of cellobiose, a common ionization pathway for carbohydrates under MALDI conditions (Chen *et al.*, 2019). Specifically, the peak at m/z 379.17 is assigned to $[Mw-2H+K]^+$, the peak at 380.18 to $[Mw-H+K]^+$, and the peak at 381.19 to $[Mw+K]^+$. The molecular weight of cellobiose ($C_{12}H_{22}O_{11}$) is 342.30 Da, and the potassium adduct at m/z 381.19 closely matches the expected value of $342.30 + 38.96 = 381.26$ Da, confirming the

successful synthesis of a disaccharide containing two glucose monomer units joined by a $\beta(1\rightarrow4)$ glycosidic bond. The slight variations in the observed m/z values relative to the calculated values fall within the accepted mass accuracy tolerance of the MALDI TOF instrument. The absence of higher order oligosaccharide peaks in the spectrum further indicates that the synthesized product is predominantly cellobiose rather than a mixture of cellulose degradation products.

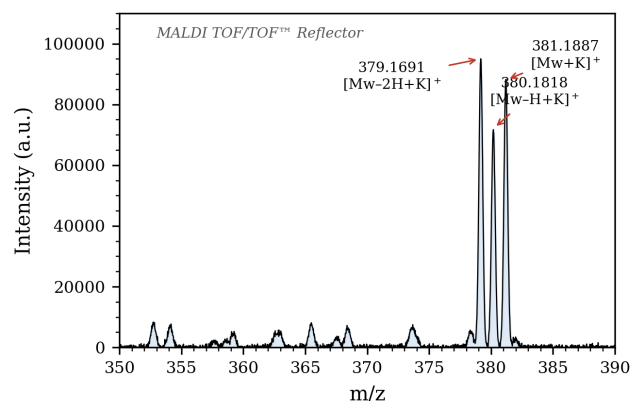


Figure 2: MALDI TOF mass spectrum of the synthesized cellobiose showing potassium adduct peaks at m/z 379.17, 380.18, and 381.19.

3.2 Physicochemical Properties of Biodiesel

The physicochemical characterization of the biodiesel produced from the transesterification of PKO with cellobiose is summarized in Table 1. The measured properties were compared against ASTM standard limits to evaluate the fuel quality and suitability for use in compression ignition engines.

Table 1. Physicochemical characterization of PKO biodiesel.

Fuel Property	ASTM Method	Value	Limits	Units
Density	D792	0.79	—	g/cm ³
Specific gravity (25 °C)	D1298	0.94	—	—
Flash point (closed cup)	D93	144	93 min	°C
Pour point	D97	-11	—	°C
Cloud point	D2500	-8	—	°C
Kinematic viscosity (40 °C)	D445	2.02	1.9–6.0	mm ² /s
Acid value	D664	0.81	0.8 max	mg KOH/g
Saponification value	—	154.86	—	mg KOH/g
Iodine value	—	10.15	120 max	g I ₂ /100 g
Peroxide value	—	660	—	Meq/kg
Refractive index	—	1.45	—	—

Water content	D664	2.10	—	%
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3.3 Flash Point

The flash point of the biodiesel was determined using a Koehler Instruments K14670 TAG closed cup flash point tester calibrated for 220 to 240 volts. The measured value of 144 °C substantially exceeds the ASTM D93 minimum requirement of 93 °C, indicating excellent thermal stability and safe handling characteristics for the produced fuel. The flash point serves as a critical regulatory parameter that governs the storage and transportation classification of petroleum products (Aly, 2019). A high flash point is especially desirable because it ensures that the fuel will not ignite at ambient or moderately elevated temperatures during storage and transfer operations. The value obtained in this study is higher than those reported for most conventional biodiesel produced via methanol based transesterification, which typically fall in the range of 100 to 130 °C (Fernando *et al.*, 2007). This elevated flash point may be attributed to the absence of residual methanol in the product, since methanol contamination is a common cause of depressed flash points in conventional biodiesel (Sanford *et al.*, 2011).

3.4 Pour Point and Cloud Point

Cold flow properties are essential indicators of biodiesel performance in temperate and cold climate applications. The pour point and cloud point of the PKO biodiesel were determined using ASTM D97 and D2500 methods, respectively, and are reported in Table 1. The pour point of -11 °C indicates that the fuel remains pourable at temperatures well below freezing, while the cloud point of -8 °C signifies the temperature at which wax crystals first become visible. These values compare favourably with those reported for palm based biodiesel in the literature (Selaimia *et al.*, 2015). The low pour point is particularly noteworthy because palm kernel oil, being rich in saturated fatty acids, typically yields biodiesel with relatively poor cold flow characteristics. The improved cold flow behaviour observed in this study may be related to the unique ester profile generated by the cellobiose transesterification pathway, which produces a mixture of ethyl, methyl, and propyl esters rather than a single ester type.

3.5 FT IR Analysis of Biodiesel

Fourier transform infrared (FT IR) spectroscopy was employed to identify the functional groups present in the biodiesel product and to confirm the successful conversion of PKO triglycerides to fatty acid alkyl esters. The recorded spectrum, spanning the wavenumber range of 4000 to 400 cm^{-1} , is presented in Figure 3, with the detailed band assignments listed in Table 2.

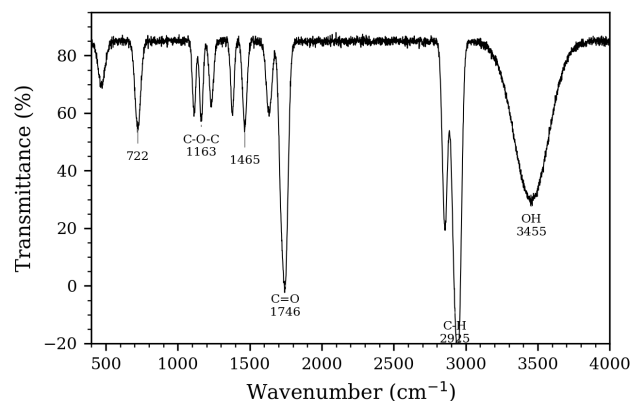


Figure 3: FT IR spectrum of biodiesel produced from the transesterification of PKO with cellobiose.

The broad absorption band centred at 3455 cm^{-1} is attributed to the O-H stretching vibration of residual hydroxyl groups, which may originate from traces of unreacted cellobiose or glycerol in the product. The strong absorptions at 2925 and 2957 cm^{-1} correspond to the asymmetric and symmetric C-H stretching modes of methylene (CH_2) groups within the long chain fatty acid backbone (Gumahin *et al.*, 2019). The intense band at 1746 cm^{-1} is characteristic of the C=O stretching vibration of ester carbonyl groups, representing the most definitive spectral evidence of successful transesterification. A weaker carbonyl absorption at 1713 cm^{-1} may indicate the presence of free fatty acids or intermediate reaction products.

The absorption bands at 1465 and 1163 cm^{-1} are of particular diagnostic significance. The band at 1465 cm^{-1} arises from the CH_2 scissoring deformation, while the band at 1163 cm^{-1} corresponds to the anti symmetric stretching of the C-O-C ester linkage. The concurrent appearance of these two bands provides compelling evidence that the triglyceride molecules in palm kernel oil have been successfully cleaved and re esterified to form fatty acid alkyl esters. The C=C stretching vibration at 1634 cm^{-1} confirms the presence of unsaturated fatty acid chains in the product mixture. The out of plane rocking vibration of CH_2 groups observed at 722 cm^{-1} is indicative of long chain aliphatic compounds, consistent with the expected fatty acid ester structure of biodiesel.

Table 2. FT IR absorption bands and functional group assignments for the biodiesel product.

Wavenumber (cm^{-1})	Functional Group	Vibration Mode	Intensity
3455	O-H (hydroxyl)	Stretching	Broad
2957	=C-H (alkyl)	Asymmetric stretching	Strong
2925	-CH ₂ (methylene)	Symmetric stretching	Strong

2855	–CH ₂ (methylene)	Asymmetric stretching	Strong
1746	C=O (carbonyl)	Stretching	Strong
1713	C=O (carbonyl)	Bending	Weak
1634	C=C (alkene)	Stretching	Weak
1465	–CH ₂ (methylene)	Scissoring	Weak
1379	–CH ₂ (methylene)	Bending	Weak
1233	–CH ₃ (methyl)	Bending	Weak
1163	C–O–C (ester)	Anti symmetric stretching	Weak
1113	C–O–C (ester)	Anti symmetric stretching	Weak
722	–CH ₂ (methylene)	Rocking	Weak

3.6 GC MS Analysis of Biodiesel

Gas chromatography mass spectrometry (GC MS) is widely regarded as the most reliable technique for determining the compositional profile of biodiesel. In this study, the analysis was performed using a Shimadzu GC MS QP2010SE instrument, and peaks were identified by comparison with the NIST 11 spectral library. The total ion chromatogram (TIC) is presented in Figure 4, and the detailed fatty acid alkyl ester profile with retention times and relative abundances is given in Table 3.

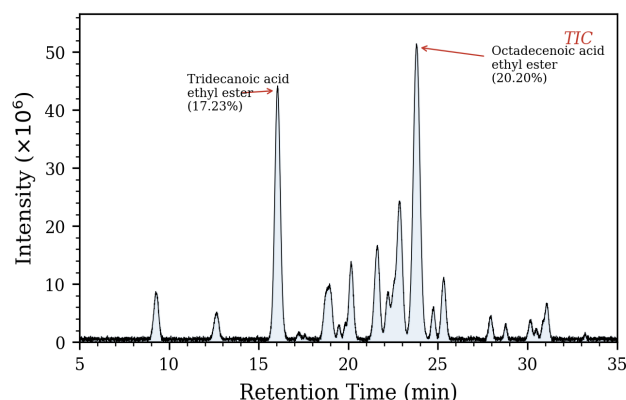


Figure 4: GC MS total ion chromatogram of the biodiesel product showing the distribution of fatty acid alkyl ester peaks.

The library matching achieved a confidence level of 99% for the vast majority of identified peaks, confirming that the product is overwhelmingly composed of fatty acid alkyl esters. The most abundant component, octadecenoic acid ethyl ester (oleic acid ethyl ester), elutes at a retention time of 23.81 min and constitutes 20.20% of the total biodiesel composition. This peak represents the C18:1 ethyl ester fraction, consistent with the

known fatty acid profile of palm kernel oil, which contains appreciable quantities of oleic acid. The second most abundant peak, tridecanoic acid ethyl ester at 16.05 min (17.23%), together with a second tridecanoic acid ethyl ester peak at 18.99 min (3.21%), reflects the contribution of medium chain fatty acids from PKO.

Table 3. Selected fatty acid alkyl ester profile of the biodiesel product.

N o.	Fatty Acid Ester	RT (min)	%
1	Octanoic acid ethyl ester	9.24	2.47
2	Octanoic acid methyl ester	9.36	1.14
3	Decanoic acid methyl ester	12.61	1.58
6	Tridecanoic acid ethyl ester	16.05	17.23
10	Tetradecanoic acid methyl ester	18.74	2.77
14	Octanoic acid methyl ester	20.16	5.15
15	Palmitic acid methyl ester	21.59	5.67
19	Stearic acid methyl ester	22.52	2.82
21	Dodecanoic acid ethyl ester	22.86	9.44
23	Octadecenoic acid ethyl ester	23.81	20.20
24	Eicosanoic acid methyl ester	24.74	2.10
25	Octadecanoic acid propanediyl	25.32	4.16

Table 4. Summary of the compositional classification of the biodiesel fatty acid alkyl ester profile.

Ester Class	Composition (%)
Fatty acid methyl esters (FAME)	22.17
Fatty acid ethyl esters (FAEE)	57.38
Fatty acid propyl esters (FAPE)	5.53
Fatty acid pentyl esters	0.25
Fatty acid hexyl esters	0.46
Fatty acid decyl esters	5.48
Fatty acid ethanediyl esters	0.98
Fatty acid propanediyl esters	4.16
Fatty acid vinyl esters	0.34
Total biodiesel yield	96.75

As summarized in Table 4, the biodiesel product consists predominantly of fatty acid ethyl esters (FAEE, 57.38%), followed by fatty acid methyl esters (FAME, 22.17%), with the remainder distributed among propyl, pentyl, hexyl, decyl, ethanediyl, propanediyl, and vinyl esters. The overall biodiesel yield was 96.75%, which is remarkably high for a solventless transesterification process. The dominance of ethyl esters over methyl esters is a notable finding, given that cellobiose is a disaccharide and does not contain methyl or ethyl groups per se.

This observation suggests that the acid catalyzed cleavage of the $\beta(1\rightarrow4)$ glycosidic bond in cellobiose generates reactive intermediates, including short chain alcohols via dehydration and rearrangement pathways, which subsequently participate in the transesterification of PKO triglycerides.

Compositional Distribution of Biodiesel

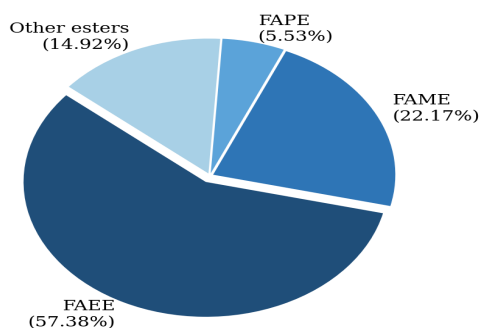


Figure 5: Pie chart illustrating the compositional distribution of the biodiesel product by ester class.

3.7 Comparative Fuel Property Analysis

To place the properties of the PKO biodiesel in broader context, selected physicochemical parameters were compared with ASTM standard limits and literature values for conventional petrodiesel. Figure 6 presents a graphical comparison of flash point, kinematic viscosity, and acid value.

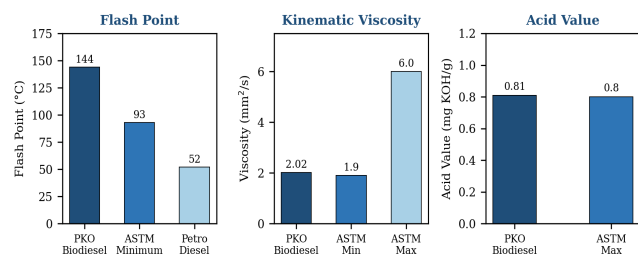


Figure 6: Comparative bar charts of flash point, kinematic viscosity, and acid value of PKO biodiesel against ASTM limits.

The kinematic viscosity of 2.02 mm²/s at 40 °C falls within the ASTM D445 acceptable range of 1.9 to 6.0 mm²/s, indicating that the fuel will flow readily through fuel injection systems and atomize properly in diesel engines. The acid value of 0.81 mg KOH/g is marginally above the ASTM D664 maximum of 0.80 mg KOH/g, suggesting that a minor additional neutralization or washing step could bring this parameter into full compliance. The saponification value of 154.86 mg KOH/g and the iodine value of 10.15 g I₂/100 g are both within acceptable ranges and reflect the predominantly saturated fatty acid composition of palm kernel oil. The low iodine value, in particular, indicates high oxidative stability, which is a desirable attribute for biodiesel storage and long term performance (Aly,

2019).

Fatty Acid Alkyl Ester Distribution

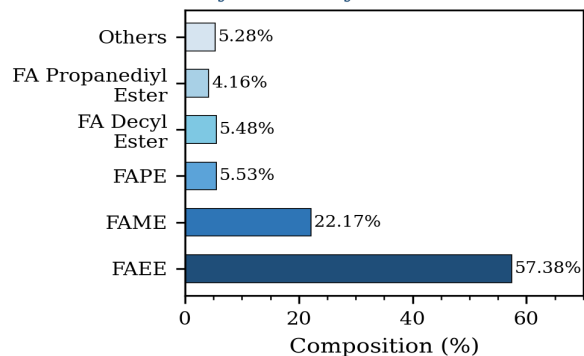


Figure 7: Horizontal bar chart showing the distribution of individual fatty acid alkyl ester classes in the biodiesel product.

The refractive index of 1.45 is consistent with values reported for biodiesel from palm based feedstocks and confirms the absence of significant contamination by unreacted oil. The density of 0.79 g/cm³ and specific gravity of 0.94 fall within the expected range for fatty acid alkyl esters and indicate a fuel that is lighter than water, facilitating the phase separation observed during the purification step. The peroxide value of 660 Meq/kg, while elevated, is not unexpected for a freshly prepared biodiesel that has not undergone stabilization with antioxidant additives. The water content of 2.10% may be attributed to the aqueous washing steps employed during purification and could be reduced through additional drying procedures.

4. Conclusion

This study has demonstrated, for the first time, that laboratory synthesized cellobiose can serve as an effective transesterification agent for the solventless green synthesis of biodiesel from palm kernel oil. The acid catalyzed reaction, conducted at 115 °C for 6 hours using concentrated HCl as catalyst, yielded 96.75% fatty acid alkyl esters without the use of methanol, ethanol, or any other conventional organic solvent. The product was authenticated by MALDI TOF MS, FT IR spectroscopy, and GC MS, all of which confirmed the successful conversion of PKO triglycerides to a biodiesel mixture dominated by fatty acid ethyl esters (57.38%) and fatty acid methyl esters (22.17%).

The physicochemical properties of the biodiesel, including a flash point of 144 °C, a pour point of −11 °C, and a kinematic viscosity of 2.02 mm²/s, fall within or close to the limits prescribed by ASTM standards for biodiesel quality. The elevated flash point, in particular, represents a significant safety advantage over conventional methanol derived biodiesel, since it eliminates the risk of residual methanol depression of the flash point. The biodiesel successfully powered a diesel engine at

B100 without blending, confirming its practical utility as a standalone fuel.

From the standpoint of green chemistry, the replacement of toxic methanol with cellobiose offers tangible environmental and occupational health benefits. Cellobiose is non toxic, biodegradable, and derivable from abundant cellulosic biomass. The solventless nature of the process further reduces waste generation, simplifies downstream purification, and lowers the overall environmental footprint of biodiesel production. Future investigations should explore the optimization of reaction parameters, including temperature, catalyst concentration, and cellobiose to oil molar ratio, to further improve yield and bring the acid value within the ASTM limit. Scale up studies and techno economic analyses will also be necessary to evaluate the commercial feasibility of this novel biodiesel production route.

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References

- [1] Aboelazayem, O., Gadalla, M. and Saha, B. (2022). Comprehensive optimisation of biodiesel production conditions via supercritical methanolysis of waste cooking oil. *Energies*, 15(10), 3766. <https://doi.org/10.3390/en15103766>
- [2] Abubakar, T.A. (2019). Thermogravimetric and differential thermal investigation of rice husk cellulose. *Bayero Journal of Pure and Applied Sciences*, 12(1), 6–11.
- [3] Aly, S.T. (2019). Synthesis and characterization of biodiesel from waste cooking oil and virgin oil. *International Journal of Engineering Research*, 8(12), 174–177. <https://doi.org/10.17577/ijertv8is120112>
- [4] Araby, E. and Araby, R. (2024). Biofuel production: exploring renewable energy solutions for a greener future. *Biotechnology for Biofuels and Bioproducts*, 17, 1–25. <https://doi.org/10.1186/s13068-024-02571-9>
- [5] Asif, M., Laghari, M., Mukwana, K.C. and Bashir, I. (2025). Pretreatment of lignocellulosic waste material conversion into biofuel and environmental impact: a comprehensive review. *Portugaliae Electrochimica Acta*, 43, 153–164.
- [6] Balat, M. (2011). Potential alternatives to edible oils for biodiesel production: a review of current work. *Energy Conversion and Management*, 52, 1479–1492. <https://doi.org/10.1016/j.enconman.2010.10.011>
- [7] Chen, J., Ma, X., Liang, M., Guo, Z., Cai, Y., Zhu, C., Wang, Z., Wang, S., Xu, J. and Ying, H. (2024). Physical, chemical, and biological pretreatment for biomass degradation and industrial applications: a review. *Waste*, 2, 451–473.
- [8] Chen, P., Shrotri, A. and Fukuoka, A. (2019). Soluble cello oligosaccharides produced by carbon catalyzed hydrolysis of cellulose. *ChemSusChem*, 12(13), 2966–2972. <https://doi.org/10.1002/cssc.201900800>
- [9] Chen, R., Qin, Z., Han, J., Wang, M., Taheripour, F., Tyner, W., O'Connor, D. and Duffield, J. (2017). Life cycle energy and greenhouse gas emission effects of biodiesel in the United States. *Bioresource Technology*, 252, 158–167. <https://doi.org/10.1016/j.biortech.2017.12.031>
- [10] Chintagunta, A.D., Zuccaro, G., Kumar, M. and Kumar, S.P.J. (2021). Biodiesel production from lignocellulosic biomass using oleaginous microbes: prospects for integrated biofuel production. *Frontiers in Microbiology*, 12, 658284. <https://doi.org/10.3389/fmicb.2021.658284>
- [11] Dias, C., Santos, J.A.L., Reis, A. and Lopes, T. (2023). The use of oleaginous yeasts and microalgae grown in brewery wastewater for lipid production and nutrient removal: a review. *Waste and Biomass Valorization*, 14(6), 1799–1822. <https://doi.org/10.1007/s12649-023-02032-8>
- [12] Donnelly, K. and Baumann, M. (2022). Continuous flow technology as an enabler for innovative transformations exploiting carbenes, nitrenes, and benzynes. *Journal of Organic Chemistry*, 87, 8279–8288. <https://doi.org/10.1021/acs.joc.2c00963>
- [13] Esi, R., Faustina, A., Kwesi, F., William, S. and Ellis, O. (2020). Effect of pretreatment on physicochemical, microbiological, and aflatoxin quality of solar sliced dried ginger. *Food Science and Nutrition*, 8(7), 5934–5942. <https://doi.org/10.1002/fsn3.1878>
- [14] Fernando, S., Karra, P., Hernandez, R. and Jha, S.K. (2007). Effect of incompletely converted soybean oil on biodiesel quality. *Energy*, 32, 844–851.
- [15] Gumahin, A.C., Galamiton, J.M., Allerite, M.J., Valmorida, R.S., Laranang, J.R.L., Mabayo, V.I.F., Arazo, R.O. and Ido, A.L. (2019). Response surface optimization of biodiesel yield from pretreated waste oil of rendered pork from a food processing industry. *Bioresources and Bioprocessing*, 6, 44. <https://doi.org/10.1186/s40643-019-0284-2>
- [16] Khan, N. and Sudhakar, K. (2021). Role of biofuels in energy transition, green economy and carbon neutrality. *Sustainability*, 13(22), 12374.
- [17] Khanna, M., Crago, C.L. and Black, M. (2011). Can biofuels be a solution to climate change? The implications of land use change related emissions for policy. *Interface Focus*, 1(2), 233–247. <https://doi.org/10.1098/rsfs.2010.0016>
- [18] Lee, D., Kim, Y., Jalaludin, I., Nguyen, H., Kim, M., Seo, J., Jang, K. and Kim, J. (2020). MALDI MS analysis of disaccharide isomers using graphene oxide as MALDI matrix. *Food Chemistry*, 323, 128356. <https://doi.org/10.1016/j.foodchem.2020.128356>
- [19] Liu, W. and Yu, H. (2022). Thermochemical conversion of lignocellulosic biomass into mass producible fuels: emerging technology progress and environmental sustainability evaluation. *ACS Environmental Au*, 2, 98–114. <https://doi.org/10.1021/acsenvironau.1c00025>
- [20] Meenakshisundaram, S., Fayeulle, A., Estelle, L., Ceballos, C. and Liu, X. (2022). Combined biological and chemical/physicochemical pretreatment methods of lignocellulosic biomass for bioethanol and biomethane energy production: a review. *Applied Microbiology*, 2, 716–734.
- [21] Ntunka, M.G., Khumalo, S.M., Makhathini, T.P., Mtsweni, S., Tshibangu, M.M. and Bwapwa, J.K. (2025). Valorization of lignocellulosic biomass to biofuel: a systematic review. *ChemEngineering*, 9(58), 1–22.
- [22] Patel, A., Karageorgou, D., Rova, E., Katapodis, P., Rova, U., Christakopoulos, P. and Matsakas, L. (2020). An overview of potential oleaginous microorganisms and their role in biodiesel and omega 3 fatty

acid based industries. *Microorganisms*, 8(434), 1–40.

[23] Ratledge, C. and Wynn, J.P. (2002). The biochemistry and molecular biology of lipid accumulation in oleaginous microorganisms. *Advances in Applied Microbiology*, 51, 1–51.

[24] Sanchez Solis, A., Lobato Calleros, O., Moreno Terrazas, R., Lappe Oliveras, P. and Neri Torres, E. (2024). Biodiesel production processes with yeast: a sustainable approach. *Energies*, 17(302), 1–37.

[25] Sanford, S., White, J., Shah, P., Wee, C., Valverde, M. and Meier, G. (2011). Feedstock and biodiesel characteristics report. Renewable Energy Group, Inc.

[26] Selaimia, R., Beghiel, A. and Oumeddour, R. (2015). The synthesis of biodiesel from vegetable oil. *Procedia: Social and Behavioral Sciences*, 195, 1633–1638. <https://doi.org/10.1016/j.sbspro.2015.06.221>

[27] Siakpebru, O.K. and Morais, A.R.C. (2026). State of the art on the conversion of lignocellulosic biomass and its derivatives into biofuels using zeolites as catalysts. *Sustainable Energy and Fuels*, 10, 1259–1281. <https://doi.org/10.1039/d5se01314c>

[28] Solaymani, S. (2023). Biodiesel and its potential to mitigate transport related CO₂ emissions. *Carbon Research*, 2, 67. <https://doi.org/10.1007/s44246-023-00067-z>

[29] Vojtov, I. and Leinweber, P. (2024). Small molecules effective for conversion of lignocellulosic biomass to furfural and its derivatives. *Biomass and Bioenergy*, 184, 107164.

[30] Wo, A., Kuligowski, K. and Swierczek, L. (2025). Review of lignocellulosic biomass pretreatment using physical, thermal and chemical methods for higher yields in bioethanol production. *Energies*, 18(2), 412.

[31] Yadav, G. and Yadav, N. (2023). Advances in biomass derived low cost carbon catalyst for biodiesel production: preparation methods, reaction conditions, and mechanisms. *RSC Advances*, 13, 23197–23210. <https://doi.org/10.1039/D3RA03561A>

[32] Yaghi, M., Chidiac, S., Awad, S. and Rayess, Y.E. (2025). An overview of biodiesel production via heterogeneous catalysts: synthesis, current advances, and challenges. *Clean Technologies*, 7(62), 1–55.

[33] Zhou, J., Lv, P., He, B., Wu, J., Wang, G., Ma, H., Wang, Y. and Chen, G. (2024). Optimisation of the ethanol fermentation process using hydrothermal pretreatment of cellulose waste. *Molecules*, 29(5266), 1–13.