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Production and Characterisation of Biodiesel from Waste Cooking Oil: A Sustainable Approach Using Transesterification

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Abstract

The present study addresses South Africa's urgent requirement for sustainable energy solutions, considering its reliance on fossil fuels and environmental issues. It explores the production and characterisation of biodiesel derived from Waste Cooking Oil (WCO) through alkali-catalysed transesterification. WCO represents a waste product that could be converted into Fatty Acid Methyl Esters (FAME) using a potassium hydroxide catalyst with methanol as the transesterifying agent. Standard physical analyses, including FT-IR spectra, were conducted to assess the biodiesel fuel quality. Fourier Transform Infrared Spectroscopy (FTIR) proved that methyl esters were synthesised by detecting ester functional groups in the biodiesel composition. The properties of WCO-biodiesel align with the American Society for Testing and Materials (ASTM) standards, such as a density of 0.870 kg/m^3, viscosity of 4.69 mm^2/s and calorific value of 38,450 kJ/kg. The rheological properties of the ternary blends containing butanol and propanol improved viscosity, shear stress and density throughout a broad temperature range. WCB 20Bu20Pr20 blend showed better physico-chemical properties as compared with other blends. The viscosity for ternary blends lies well within the range prescribed by ASTM D6751, i.e. 1.9 - 6.0mm^2/s at 40°C, with WCB20Bu15Pr15 and WCB20Bu20Pr20 having very favourable values of 2.371 mm^2/s and 2.320 mm^2/s, respectively. This study demonstrates how WCO can be transformed into clean-burning biofuels that provide a sustainable solution to South Africa's energy security needs and environmental protection goals.

Major Findings: *WCB exhibited a reduced viscosity (from 31.62mm^2/s to 4.69mm^2/s), a modestly increased calorific value (38,450 kJ/kg), and a safer flash point (89.5°C) compared to diesel. The ternary blends (WCB20Bu10Pr10, WCB20Bu15Pr15, WCB20Bu20Pr20) exhibited favourable rheological behaviour in terms of reduced viscosity, shear stress, and density at elevated temperatures. WCB20Bu20Pr20 demonstrated the most desirable characteristics that include low viscosity (1.004mm^2/s at 90°C), minimal shear stress (0.759 Pa), and reduced density (0.771 g/cm^3).*

Keywords: *Biodiesel, Characterisation, Transesterification, Waste Cooking Oil*

1.0 Introduction

Amid intensifying energy insecurity and environmental degradation, South Africa remains disproportionately reliant on fossil fuels, an unsustainable trajectory with far-reaching climate implications. The country is facing more problems of fuel shortage, frequent load shedding, and fuel price instability that affect economic development and energy security[1,2]. As the global and national targets for carbon emission reduction are becoming more stringent, it is crucial to shift towards renewable energy sources[3,4]. Biodiesel, produced from (WCO), is a viable alternative with advantages of environmental and economic benefits[5]. The investment in biofuels can assist South Africa to

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diversify its energy supply, increase the sustainability and decrease the reliance on fossil fuels. Being a member of the Paris Agreement, South Africa is committed to decreasing its carbon footprint through the integration of renewable energy sources in the energy sector by introducing the 'Biofuels Industrial Strategy[6]. The use of WCO for biodiesel production is also in conformity with these policies, as well as the environmental issues of waste disposal.

WCO represents a waste stream of the food sector and can be obtained easily in large quantities from restaurants, fast food outlets and even homes across South Africa. Sharma *et al.*[7] suggested that, if WCO is not handled properly, it can pose a great threat to the environment through consequences such as pollution of water and soil, blocked drainage systems and piling up as waste in landfills. Many businesses still discard used cooking oil irresponsibly, which leads to pollution and potential health risks[8]. Additionally, WCO-based biodiesel is cost-effective compared to virgin oil-based biodiesel, which makes it a more accessible option for sustainable fuel production[9].

Against this backdrop, the transesterification of WCO has emerged as a viable technical pathway for biodiesel synthesis. The global interest in producing biodiesel from WCO is increasing because of its sustainability, cost-effectiveness, and environmental benefits. Many countries are exploring WCO as a viable feedstock to reduce fossil fuel dependence, lower greenhouse gas emissions, and promote circular economy practices in renewable energy development[10]. The widely used method in producing biodiesel is transesterification, in which the triglycerides in WCO react with methanol in the presence of a catalyst such as Potassium hydroxide (KOH) or Sodium hydroxide (NaOH) that converts oils into biodiesel (methyl esters) and glycerol as a byproduct[11,12]. Catalysts play an important role in improving yield in biodiesel production through transesterification. Alkaline catalysts such as KOH and NaOH are widely used due to their high reaction rates and cost-effectiveness[13]. Nonetheless, they require low Free Fatty Acid (FFA) content in feedstock. Acidic catalysts such as H_2SO_4 are effective for high-FFA oils but have slower reaction rates[14,15]. Enzymatic catalysts such as lipases offer a sustainable alternative with high selectivity and mild reaction conditions, but are expensive and require longer reaction times[16]. Selecting the appropriate catalyst depends on feedstock composition, process conditions, and desired biodiesel yield. Optimising the reaction parameters in biodiesel production is essential for maximising the yield[17]. Temperature in the range of 50-65°C accelerates transesterification, and optimal catalyst concentration assures efficient conversion[18]. The alcohol-to-oil molar ratio determines the extent of the transesterification reaction[19]. Properly balancing these factors enhances biodiesel quality, reduces byproducts, and improves overall process efficiency[20].

Various studies on the biodiesel production from WCO through esterification and transesterification methods are very well documented. The research shows that alkaline catalysts such as KOH and NaOH achieve superior conversions in biodiesel production, but their effectiveness depends on low FFA content, while acid catalysts function well with high FFA oils[21,22]. Various investigations show that biodiesel production levels alongside fuel quality depend on key reaction variables, which include temperature, catalyst dose, and alcohol-to-oil ratio[23]. Enzymatic catalysis demonstrates great potential for sustainable production, yet it continues to be expensive. The test results indicate that Waste Cooking Oil Biodiesel (WCB) serves as an alternative fuel because it passes both EN 14214 and ASTM D6751 standards[24]. The industrial production methods need additional improvement to overcome current challenges. The yield of biodiesel from WCO is strongly dependent on the process parameters[25]. Using KOH and NaOH alkaline catalysts gives yields of 90-98 % at high temperatures of 60°C and a 6:1 methanol to oil ratio[22]. Enzymatic catalysts are a sustainable alternative but have lower reaction rates. The final yield is also influenced by efficient separation and purification processes[26]. These factors need to be optimised to get the maximum biodiesel recovery and to ensure that the fuel quality standards are met.

The biodiesel production utilises KOH and NaOH as homogeneous catalysts because they provide fast reaction rates along with economical operation. The catalysts need extensive purification because they dissolve in the reaction mixture, which results in soap formation and catalyst loss. The separation process for heterogeneous catalysts such as metal oxides and solid acids becomes simpler while their reusability improves and wastewater production decreases[27]. The environmental advantages and process efficiency of these catalysts come at the

expense of reduced reaction rates, which necessitate elevated temperatures and extended reaction durations. The selection between homogeneous and heterogeneous catalysts depends on three main factors, which include feedstock composition and process cost and sustainability considerations[28,29].

The production of biodiesel from WCO has been the subject of many studies, but there are still areas that need to be addressed to improve the efficiency of the process without compromising the environmental trade-offs. This study presents a sustainable transesterification process that has been developed for the South African context, with a focus on catalyst selection, yield optimisation, and the characterisation of biodiesel properties.

This study aims to investigate the production of biodiesel from WCO via alkali-catalysed transesterification and to characterise its fuel properties in comparison with conventional diesel. The research also investigates ternary blending of WCO biodiesel with butanol and propanol to enhance key rheological properties including viscosity, density and shear behaviour. Adding short-chain alcohols in regulated amounts (10–20 %) is hypothesised to improve the cold flow characteristics and general fuel performance, hence making the blends for use in diesel engines. By linking fuel characterisation to expected engine behaviour, this work aims to bridge the gap between sustainable biofuel production and practical diesel engine applications in South Africa.

2.0 Materials and Methods

2.1 Materials Used

KOH was acquired from Jezreel Eduscience, South Africa. WCO was obtained from the cafeteria at the University of South Africa, Science campus. Biodiesel derived from WCO was produced using the transesterification process, using methanol as a reagent and KOH as a catalyst.

2.2 Biodiesel Production

The technique outlined by Aworanti *et al.*[30] was used to assess the FFA in WCO. The FFA was quantified using titration to measure the precise quantity of catalyst to provide accurate results and prevent fuel wastage. One gram of KOH was solubilised in one litre of distilled water. 10ml of isopropyl alcohol was added into 1ml of WCO. Three drops of phenolphthalein indicator were added to create a colourless solution. The combination of distilled water and KOH was thereafter placed in a burette and titrated with the white solution until a pink colour was seen. The titration procedure was conducted three times to ascertain the average quantity of KOH used in the titration. The outcomes of the first, second, and third titrations were 2.4ml, 3.4ml, and 2.4ml, respectively. The average volume was 2.7ml, which was deemed adequate to advance with the transesterification process for biodiesel production from WCO[31].

The most significant and efficient method for biodiesel production is the transesterification of oils with alcohol to yield biodiesel as the primary product and glycerin as a byproduct. The biodiesel pilot plant supplied by Pignat® (Figure 1) was used in the present study to produce biodiesel. The oil was filtered using a 200ml fuel funnel to eliminate solid contaminants. The oil was heated to 100°C to eliminate the water content. The absence of water and contaminants was essential for effective transesterification processes. Methanol was used for the reaction due to its cost-effectiveness relative to other alcohols and its superior physicochemical features. KOH was used as a very effective reagent in transesterification operations. The oil temperature had been set at 55°C in the heating tank prior to the commencement of the reaction. The prepared solutions of methanol and KOH catalyst (9:1) were combined in the reactor tank and stirred. The whole test was conducted at a temperature of 55°C for a duration of one to two hours. The mixture was left to settle or cool overnight to facilitate the separation of biodiesel and glycerol. The oil methyl ester ascended to the top layer of the separation tank, while the glycerol descended to the bottom layer. The biodiesel was purified with warm distilled water to remove contaminants and glycerin. The tank lid was opened, and 50% of the volume of distilled water was introduced into the ester and swirled gently. After five minutes, the drain valve was opened to retrieve the soapy water from the container. The washing process was conducted until the bottom layer had a pH comparable to that of pure water, indicating that the biodiesel fuel was free of catalysts. The biodiesel drying process required a minimum of 4-5 hours during agitator operation. After 4-5 hours, the mixture was cooled by adjusting the thermoregulatory

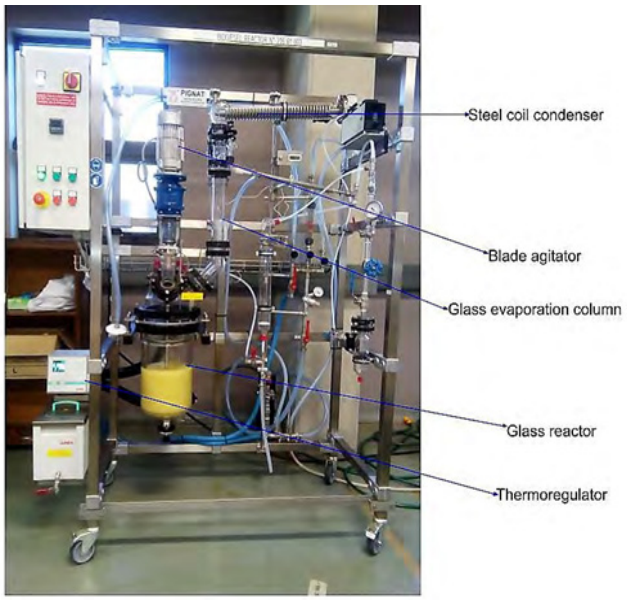


Figure 1. Biodiesel pilot plant.

setting to 20°C. When the temperature was below 20°C, the valve was opened to collect the biodiesel in a suitable container. Glycerol generated as a byproduct of biodiesel production is a versatile compound with significant industrial value. After appropriate purification, glycerol can be utilised in pharmaceuticals, cosmetics, the food industry, the chemical industry, animal feed, and green solvent.

2.3 Blending of Fuel Samples

The in-tank blending method was applied to prepare standard diesel (D100), WCB and hybrid alcohol blending using butanol and isopropanol in proportions of 10%, 15%, and 20% (WCB20Bu10Pr10, WCB20Bu15Pr15, WCB20Bu20Pr20, B20) in different tanks as indicated in Figure 2. The WCB and diesel were poured on top of the butanol and isopropanol fuel surface. This method improved the blending of butanol-isopropanol and WCB-diesel and avoided the settling down of the WCB and diesel at the lower end of the tank due to its higher density[32]. The lid tank was closed tightly and agitated for three minutes. The complete butanol-isopropanol and WCB-diesel were finally poured into the fuel tank that connects the fuel supply system. The 10%, 15%, and 20% alcohol blending levels were selected based on the miscibility behaviour, cold flow improvement, and fuel standards. A mixture of butanol and propanol at volumes less than 20% effectively enhances the cold flow properties of biodiesel-diesel blends while reducing viscosity without leading to phase separation issues. The specified range of alcohol concentrations helps to keep the final blends within the acceptable limits of density, viscosity and calorific value as per ASTM D6751 and EN 14214 standards. The chosen ratios combine to enhance diesel engine operational properties and maintain blend durability along with optimal combustion

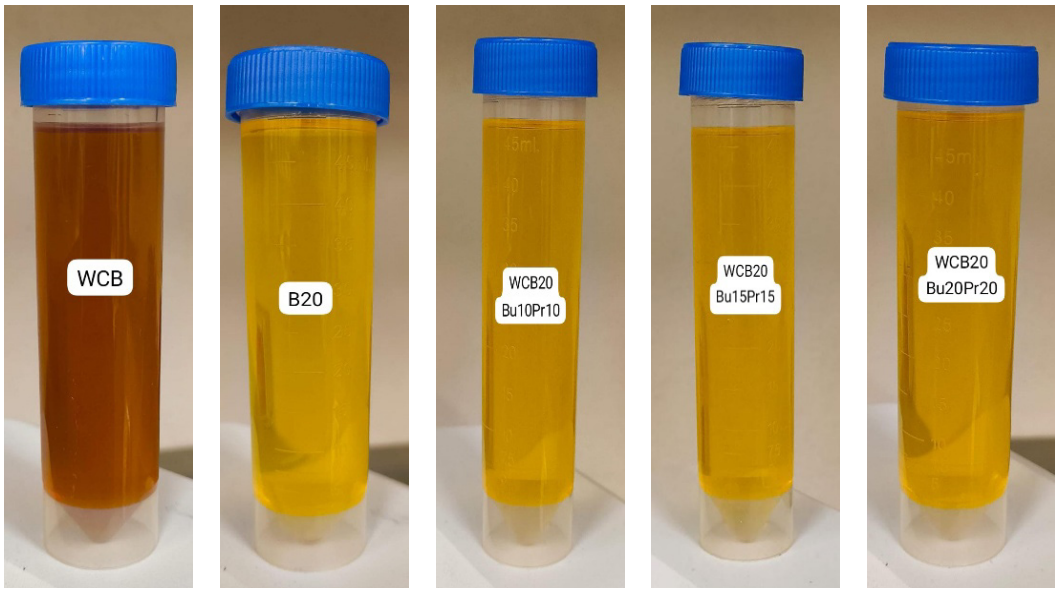


Figure 2. The samples of fuel produced.

Table 1. The nomenclature of fuel blends

S. No.	Fuel Blend	Diesel (Vol. %)	WCB (Vol% %)	Butanol (Vol. %)	Isopropanol (Vol. %)
1	D100	100	0	0	0
2	WCB	0	100	0	0
3	B20	80	20	0	0
4	WCB20Bu10Pr10	60	20	10	10
5	WCB20Bu15Pr15	50	20	15	15
6	WCB20Bu20Pr20	40	20	20	20

operation. The samples of test fuels are presented in Figure 2.

2.4 Characterisation of WCB

The characterisation of the produced WCB was done to assess its mechanical properties and some important physicochemical properties that will help in determining its potential as a diesel substitute. Two major categories of analysis were performed: Functional groups identification by FTIR and thermal-rheological profiling by automated viscometry.

FTIR analysis was carried out using the Bruker Vertex 70 FTIR spectrometer to confirm the conversion of triglycerides into FAMEs through transesterification.

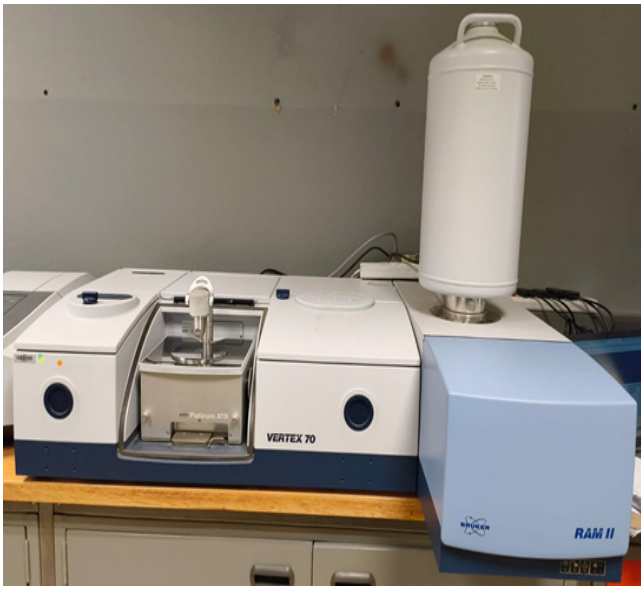


Figure 3. The photographic view of FTIR.



Figure 4. The photographic view of the viscometer (Specifications of FTIR to be included).

The WCB sample was scanned in the mid-infrared range (4000–400 cm^{-1}), and the resulting spectrum was evaluated for characteristic absorption bands. The rheological characterisation of WCB and its blends was done using an Anton Paar SVM 3001 Viscometer that allowed for the accurate and simultaneous measurement of kinematic viscosity, density, shear stress and shear rate in the temperature range of 30°C to 90°C. The

photographic views of FTIR and viscometer are presented in Figures 3 and 4.

These measurements provide a comprehensive profile of WCB and its blends that confirm the thermo-rheological advantages of alcohol modification and validate their potential as high-performance, renewable diesel fuels.

3.0 Results and Discussion

3.1 Estimation of Yield

The yield of biodiesel is an important factor in determining the technical practicability and economic efficiency of the transesterification process. In this study, the yield was determined by the mass of the purified biodiesel collected after separation and washing, about the initial mass of WCO used for the reaction. The biodiesel yield (%) was calculated using the formula mentioned in Equation 1.

$$Biodiesel\ yield\ (\%) = \left(\frac{W_{biodiesel}}{W_{oil}}\right) \times 100 \quad (1)$$

is the amount of biodiesel produced after purification and is the initial amount of WCO used.

The yielded biodiesel analysis contains only the final purified product after removing glycerol, residual alcohol, catalyst and water from the mass calculation. A repeated washing process and complete sample drying took place before the mass determination procedure. The yield determination adopted a ±2% sensitivity since small amounts of moisture, along with residual methanol and soap formation, could lead to minor yield reduction. The yield obtained in the present study is 92%. This yield aligns with literature-reported values for alkali-catalysed transesterification of low-FFA feedstocks that typically range between 90–98% under optimised conditions of temperature, molar ratio, and catalyst dosage[33].

3.2 FT-IR Analysis of Biodiesel

The FT-IR spectrum of WCB, as shown in Figure 5, shows clear peaks that are characteristic of FAME, which indicates that the transesterification of WCO was successful. This spectral fingerprint allows for to identification of the key functional groups that define the molecular structure of biodiesel. The peak intensities in the FTIR are compared qualitatively. The most significant and diagnostic absorption band is observed at 1743cm^{-1} which is assigned to the C=O stretching vibration of ester carbonyl groups and is a clear indicator of the formation of methyl esters. This peak is not observed in untreated cooking oils, where the dominant carbonyl band is observed at 1708cm^{-1} due to triglyceride content. Similar findings were observed in the FT-IR analysis of WCB by Khan *et al*[34]. The appearance of the 1743cm^{-1} band thus indicates the breaking of triglycerides and the formation of methyl esters. Complementing this are two sharp peaks at 2923cm^{-1} and 2854cm^{-1} assigned to the asymmetric and symmetric C–H stretching vibrations of aliphatic –CH_2–groups. These bands confirm the long hydrocarbon chains typical of biodiesel, like those found in petroleum diesel, but originate from a renewable biomass source. Further supporting the ester identity, the band at 1215cm^{-1} is indicative of C–O stretching vibrations in esters, while the peaks at 1438cm^{-1} and 1461cm^{-1} are associated with CH_2 bending vibrations that are consistent with saturated aliphatic chains. The 1361cm^{-1} band is due to CH_3 symmetric bending, i.e., a recurring feature in methyl ester compounds. The region below at 1168cm^{-1} and 879cm^{-1} reflects fingerprint vibrations from C–O–C and C–H out-of-plane bending that reinforce the aliphatic ester structure[35]. Peaks at 721cm^{-1}

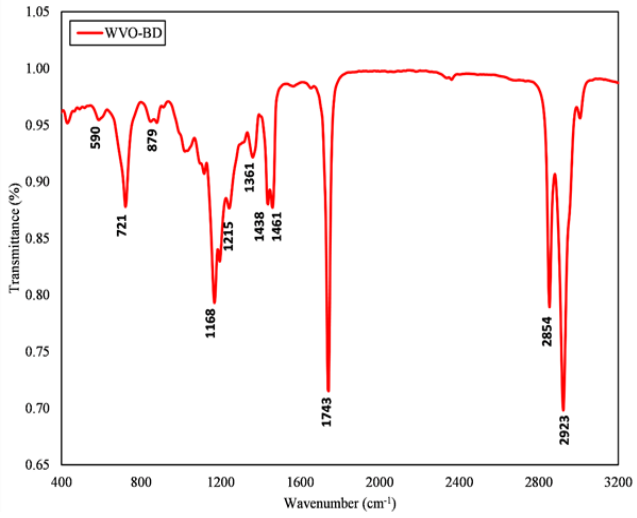


Figure 5. FT-IR spectrum of waste cooking oil biodiesel.

and 590 cm^{-1} further highlight the wagging and twisting modes of long-chain alkanes that indicate hydrocarbon-rich molecular composition. The absence of a broad absorption band in the 3300 - 3500cm^{-1} region affirms the absence of free hydroxyl groups, which implies low levels of residual methanol and FFA. This is desirable for fuel stability and compliance with ASTM D6751/EN 14214 standards.

3.3 Properties and Quality of Biodiesel

Table 1 shows the comparative analysis of the main physicochemical properties of diesel, WCO, and WCB that are important for assessing the potential of WCB as a diesel engine fuel.

The density of WCO (0.916 kg/m^3) is observed to be higher than that of diesel (0.840 kg/m^3), which can be attributed to the presence of FFA, glycerides, and other heavy organic compounds[36]. After transesterification, the density of WCB is reduced to 0.870 kg/m^3, which is closer to diesel. This reduction indicates successful conversion of triglycerides into methyl esters that improve their suitability as a diesel substitute.

Viscosity plays an important role in fuel atomisation and combustion. WCO exhibits a very high kinematic viscosity (31.62mm^2/s) that could lead to poor fuel

Table 1. The properties of WCO and WCB

S. No.	Property	Diesel	WCO	WCB	Instrument Used	ASTM Standard
1	Density (kg/m^3) @40 ^{0}C	0.840±0.5	0.916±0.2	0.870±0.3	SVM 3001 Cold Properties; Anton Paar	ASTM D4052
2	Kinematic viscosity mm^2/s @40 ^{0}C	2.12±0.02	31.62±0.5	4.69±0.2	SVM 3001 Cold Properties; Anton Paar	ASTM D445
3	Calorific value (kJ/kg)	46500±150	36520±23	38450±36	e2K oxygen bomb calorimeter	ASTM D240
5	Flash point (^{0}C)	54±0.5	272±5.5	89.5±3.5	Automatic flash point tester, Pensky Martens, Scavini.	ASTM D93
6	Carbon content (%)	85±0.2	-	78.92±1.1	FLASH 2000 CHNS/O Analyzer, Thermo Scientific	ASTM D6291
7	Nitrogen content (%)	0±0.0	-	11.76±0.5	FLASH 2000 CHNS/O Analyser, Thermo Scientific	ASTM D6291
8	Hydrogen content (%)	13±0.1	-	0.18±0.03	FLASH 2000 CHNS/O Analyser, Thermo Scientific	ASTM D6291
9	Oxygen content (%)	0±0.0	-	9.11±1.1	Difference of C, H, N, and S (FLASH 2000 CHNS/O Analyser, Thermo Scientific)	ASTM D6291 (Calculated)

atomisation, increased injector clogging, and incomplete combustion[37]. The transesterification process reduces the viscosity to 4.69mm²/s, which is slightly higher than diesel (2.12mm²/s). This is within the acceptable range for biodiesel fuels that ensure better flow properties and improved spray characteristics.

The calorific value of WCO is 36,520 kJ/kg and is much lower than diesel at 46,500 kJ/kg. This could be attributed to its higher oxygen content and the presence of triglycerides[38]. The calorific value of WCB increases to 38450 kJ/kg post-transesterification, indicating enhanced energy content. This indicates that biodiesel offers somewhat lower energy per unit mass. However, it may serve as a feasible alternative with enhanced combustion efficiency.

The flash point of WCO is very high (272°C), making it much safer to store and handle compared to diesel (54°C). After transesterification, the flash point decreases to 89.5°C and is higher than diesel, which indicates improved safety while maintaining better ignition characteristics[39]. The elevated flash point of biodiesel makes it safer for transportation and storage and reduces the risk of accidental fires.

The carbon content of WCB amounts to 78.92%, while diesel contains 85% carbon, which results in lower emissions and improved combustion performance. WCB contains 11.76% nitrogen while diesel has 0% nitrogen, which potentially results in increased NO_x emissions. WCB obtains its substantially decreased hydrogen content of 0.18% because hydrocarbon chains break down during transesterification, leading to modified combustion properties. WCB contains 9.11% oxygen, which improves the combustion process and minimises soot emissions while it promotes enhanced NO_x formation owing to higher combustion temperature.

3.3.1 Viscosity Variations with Respect to Temperature

Atomisation, mixing, and combustion efficiency of biodiesel and its blends are governed by kinematic viscosity. Figure 6 shows the variation of kinematic viscosity with temperature for WCB, B20 blends and the ternary blends WCB20Bu10Pr10, WCB20Bu15Pr15, and WCB20Bu20Pr20. The results demonstrate a continual downward trend across all fuels with increasing temperature that is attributable to the enhanced molecular mobility and reduced intermolecular forces at elevated thermal conditions. The highest viscosity value of 5.8856 mm²/s occurred at 30°C because WCB contains long-chain fatty acid esters and residual FFA, which are typical for neat biodiesel[40]. The addition of petroleum diesel to WCB resulted in B20 with a viscosity measurement of 3.598mm²/s because petroleum diesel acts as a viscosity reducer. The viscosity decreases even more when low molecular weight alcohols such as butanol and propanol are added to create ternary blends.

WCB20Bu20Pr20 exhibited the lowest viscosity over all temperature ranges, i.e., 2.857mm²/s at 30°C and decreases to 1.004 mm²/s at 90°C. This highlights the effect of butanol and propanol as oxidising agents to lower viscosity[41]. Their comparatively low viscosity and increased volatility improve the flow characteristics of the blend at low and moderate temperatures. A gradual decrease in viscosity is seen in the ternary blends with increasing alcohol content, indicating the beneficial effect of alcohol. The viscosity gap between WCB and WCB20Bu20Pr20 is quite large at lower temperatures, i.e., 3.0286 mm²/s at 30°C, but this gap narrows gradually at higher temperatures. At 90°C, the viscosity difference reduces to 1.041mm²/s. This convergence suggests that at higher operating temperatures typical of compression

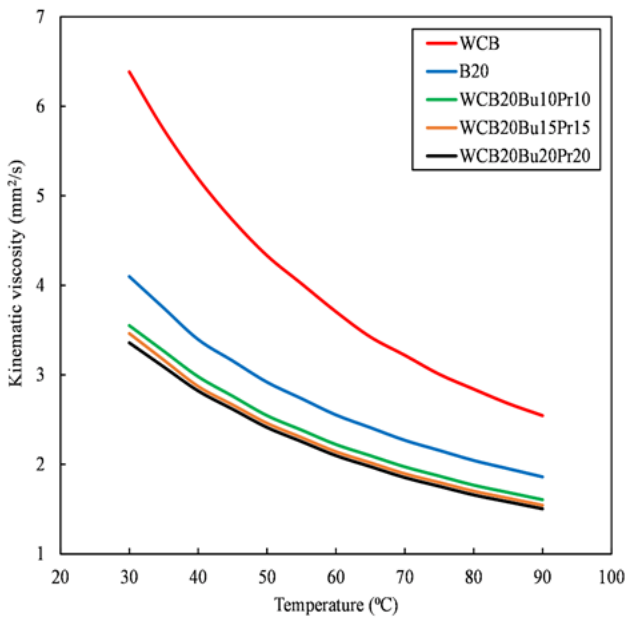


Figure 6. Kinematic viscosity variations with respect to temperature of fuels.

ignition engines, the effect of the initial feedstock viscosity becomes less significant and blend homogeneity becomes more important in flow dynamics.

All the observed values of viscosity for ternary blends lie well within the range prescribed by ASTM D6751, i.e. 1.9-6.0mm²/s at 40°C, with WCB20Bu15Pr15 and WCB20Bu20Pr20 having very favourable values of 2.371mm²/s and 2.320mm²/s, respectively. This implies higher atomisation potential without losing lubricity. Specifically, the reduction in viscosity below 2.0mm²/s at temperatures above 70°C indicates that the fuels of interest have unusually high viscosity reduction potential below 2.0mm²/s for high-speed diesel engines operating at elevated thermal load.

3.3.2 Shear Rate Variations with Respect to Temperature

Shear rate is an important rheological parameter that is relevant to the flow behaviour of fuel under mechanical stress in high-pressure fuel injection systems. The results of the data presented in Figure 7 show the temperature-dependent variation in shear rate for WCB, B20, and the ternary blends (WCB20Bu10Pr10, WCB20Bu15Pr15, WCB20Bu20Pr20). All fuel samples show an increasing trend in shear rate with rising temperature that is consistent with the thermally induced reduction in viscosity. At 30°C, WCB shows the lowest shear rate (697.8 s^{-1}) that reflects its higher resistance to deformation. This is a direct result of its viscous properties and the presence of larger molecular weight molecules. B20 shows a shear rate of 826.36 s^{-1} at the same temperature, which is ascribed to its reduced viscosity and enhanced flowability resulting from diesel dilution[42].

The addition of butanol and propanol in the ternary blends further augments the shear rate values. At 30°C, WCB20Bu10Pr10, WCB20Bu15Pr15, and WCB20Bu20Pr20 record values of 854.42, 863.25, and 866.76 s^{-1}, respectively. This progressive enhancement in shear rate aligns well with the increasing proportion of oxygenated alcohols with low viscosity. These alcohols act as co-solvents that break down intermolecular interactions among triglycerides and esters, leading to smoother flow and lower resistance to shear forces. The differences in shear rate between WCB and the ternary blends become increasingly pronounced with temperature. At 60°C, the shear rate for WCB is 812.5 s^{-1} and for WCB20Bu20Pr20

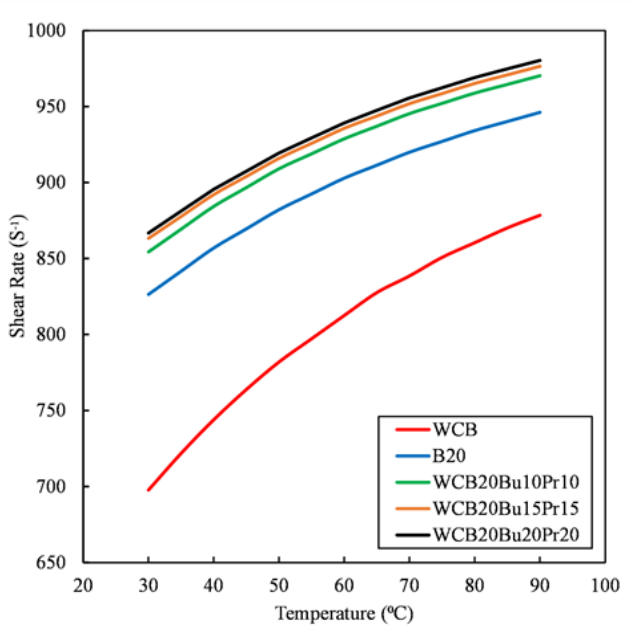


Figure 7. The variations of shear rate with respect to temperature.

reaches 939.21 s^{-1} with an increase of over 15%, which highlights the improved fluidity and flow behaviour of alcohol modified blends under thermal excitation. At elevated temperatures like 90°C, all fuel types achieve their peak shear rates, with WCB20Bu20Pr20 attaining 980.31 s^{-1}.

The trends also illustrate that ternary blends are less sensitive to temperature-induced viscosity increase and maintain superior shear performance even at lower thermal inputs. This implies enhanced cold flow properties that are advantageous during cold start engine conditions. In addition to that, the increment in shear rate with alcohol addition indicates better rheological tuning of fuel blends that render them more suitable for high-speed diesel engines, where rapid injection and fine atomisation are vital.

3.3.3 Shear Stress Variations with Respect to Temperature

Shear stress functions as a fundamental rheological property because it measures the intrinsic resistance of a fluid to deformation when an external force is applied. The shear stress controls fuel flow through injectors, subsequently affecting atomisation and

spray characteristics before influencing combustion behaviour. The shear stress values of WCB, B20 and the ternary blends (WCB20Bu10Pr10, WCB20Bu15Pr15, and WCB20Bu20Pr20) show their relationship with temperature according to Figure 8. The shear stress for all fuel samples tested shows similar trends at all temperatures and confirms that the fluid resistance decreases due to thermally activated effects and affirms Newtonian behaviour in the tested fuels over the measured range[43]. The WCB showed the highest shear stress (3.607 Pa) at 30°C, followed by B20 (2.411 Pa), and a decreasing shear stress with the increase of the alcohol content of the ternary blends. In line with the viscosity and shear rate results, the viscosity (η) is directly proportional to the shear rate (γ). Thus, the shear stress (τ) increases with the shear rate as per the Equation 2.

$$\tau=\eta\times\gamma \quad (2)$$

The shear stress exerted by the fluid is directly proportional to the shear rate, with viscosity acting as the proportionality constant. This linear relationship confirms that biodiesel and its blends exhibit Newtonian flow behaviour across the studied temperature range.

As temperatures increased to 90°C, the shear stress of WCB dropped to 1.499 Pa, which indicates a 58.5% reduction. B20, WCB20Bu10Pr10, and WCB20Bu20Pr20 reduced to 1.008 Pa, 0.832 Pa, and 0.759 Pa, respectively. The magnitude of these reductions emphasises the superior flowability of the alcohol enhanced blends at elevated temperatures. Shear stress values of WCB20Bu20Pr20 are the least in all thermal conditions. When compared to WCB under the same conditions, WCB20Bu20Pr20 shear stress was 47% less, with a value of 1.195 Pa, whereas the WCB shear stress was 2.230 Pa. This pronounced decline can be traced to the addition of butanol and propanol, which disrupts the internal cohesion and thereby reduces resistance to flow. Additionally, the alcohols have lower intrinsic viscosities and higher volatilities than the base biodiesel components, so that they also provide enhanced molecular slippage under shear.

Shear stress decline rate is faster at lower temperatures (30–60°C) than at higher temperatures (65–90°C). This shows that the various improvement of low temperature flow behaviour enhances the use of alcoholic biodiesel in cold climates or during cold engine start. The decreasing shear stress trends with increasing temperature and decreasing amounts of alcohol content demonstrate that ternary blends not only have more favourable temperature and rheological properties but may also be more injection and atomization efficient. Specifically, these features lead to tighter fuel sprays for better air-fuel mixing and more complete combustion, which makes such spark ignition engines desirable in compression ignition engines for improved efficiency and lower emissions.

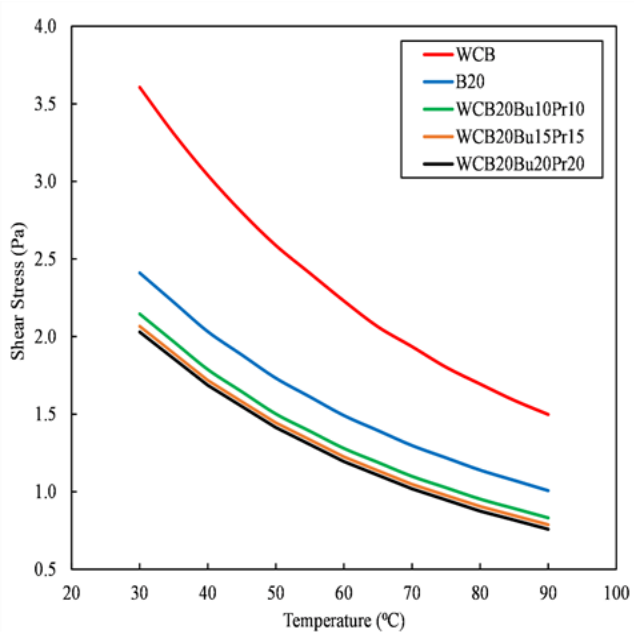


Figure 8. The variations of shear stress with respect to temperature.

3.3.4 Density Variations with Respect to Temperature

The physical property of density directly affects the volumetric energy content, together with spray characteristics and atomisation behaviour of fuels in diesel engines. Figure 9 shows how density changes with temperature for WCB, B20, and ternary blends of butanol and propanol (WCB20Bu10Pr10, WCB20Bu15Pr15, WCB20Bu20Pr20). The density for all fuel samples continually decreased with increasing temperature. The combined behaviour of this is thermodynamically anticipated since expansion of fluid volume with heat is accompanied by a decrease in mass per unit volume. With the highest density of 0.8782 g/cm^3 at 30°C, WCB

is reflective of its higher molecular weight esters and unrefined components compared with the base oils[44]. The ternary blends further reduced the value of the density (0.831 g/cm³) of WCB20Bu20Pr20 compared to B20 (0.820 g/cm³).

The dilution of B20 with butanol and propanol imparted a density-lowering effect that is attributed to the lower molecular mass and volatility of these alcohols compared to biodiesel and diesel constituents. Among the blends, WCB20Bu15Pr15 and WCB20Bu20Pr20 consistently demonstrated the lowest density values at every temperature point. At 60°C, WCB20Bu20Pr20 registered a density of 0.796 g/cm³ compared to 0.856 g/cm³ for WCB and 0.805 g/cm³ for B20, which represents a density reduction of nearly 7% relative to pure biodiesel.

The reduction in density has dual implications. On one hand, it may reduce the volumetric energy content that could have a small effect on brake thermal efficiency under certain operating conditions. On the other hand, lower density results in smaller droplets and better air-fuel mixing in high-speed diesel engines, where good combustion depends on droplet dispersion[45]. The convergence in density values across all blends at higher temperatures, i.e., at 90°C suggests that the influence of alcohol content becomes less pronounced at elevated thermal levels. At 90°C, the difference between B20 (0.784 g/cm³) and WCB20Bu20Pr20 (0.771 g/cm³) is merely 0.013 g/cm³ that indicate, temperature becomes the dominant variable governing density[46]. The observations show that alcohol based ternary blends have favourable fuel properties in terms of viscosity and shear behaviour as well as density profiles that meet international standards such as ASTM D6751 and EN 14214. The ability to tailor density through alcohol blending presents a versatile tool for optimising fuel formulations according to specific engine and climate requirements.

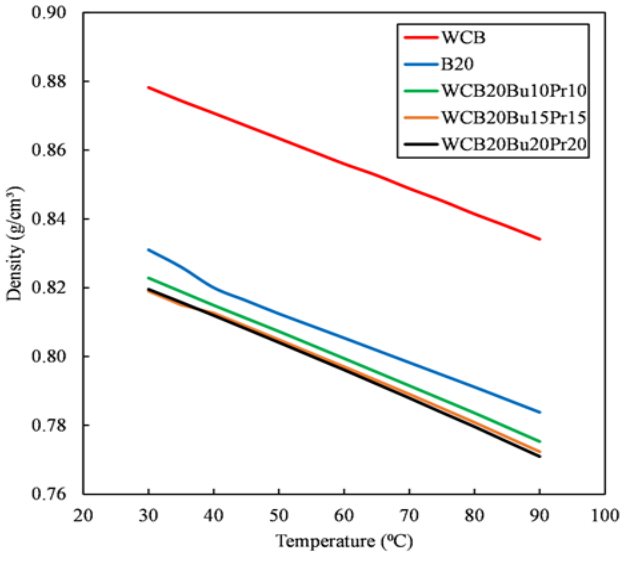


Figure 9. The variations of density with respect to temperature.

3.4 Relevance of Fuel Properties To Engine Testing

The characterised fuel properties provide strong indications of engine behaviour. The WCB and ternary blends show reduced viscosity and lower density, which should enhance fuel atomization and spray quality that could result in better air-fuel mixing and more complete combustion[47]. The moderate calorific value of WCB suggests slightly lower energy output compared to diesel[4]. However, the improved oxygen content in the biodiesel is likely to promote cleaner combustion with lower particulate matter emissions[11,48]. The increased flash point ensures storage and handling safety while maintaining engine ignition properties in compression engines[49,50]. Overall, the rheological improvements achieved through alcohol blending in WCB20Bu20Pr20 suggest favourable cold flow properties and efficient in-cylinder combustion behaviour. These fuels could be highly promising for practical diesel engine applications.

3.5 Correlation Between Rheological Properties and Engine Behaviour

The rheological properties studied in this work, such as kinematic viscosity, shear stress, shear rate, and density, have a direct influence on the performance of diesel engines. Lower viscosity fuels and reduced shear stress result in finer atomisation and narrower droplet size distribution during injection, which enhances air-fuel mixing and combustion efficiency[15]. Research indicates that biodiesel blends with lower viscosity lead to better fuel spray penetration and faster evaporation, which produces complete combustion and reduces particulates in the emissions[18,23,31]. The reduced density helps to improve spray dispersion, but it may slightly reduce volumetric energy content[34]. The improved cold flow

behaviour observed in ternary alcohol blends such as WCB20Bu20Pr20 indicates better cold start performance and less injector fouling, which are important for reliable diesel engine operation under different ambient conditions.

4.0 Conclusions

This study demonstrated the conversion of WCO into high-quality biodiesel through an alkali-catalysed transesterification process using potassium hydroxide and methanol. The transformation of WCO into FAME was validated through FT-IR spectral analysis that confirmed the presence of key ester functional groups to affirm the compositional integrity of biodiesel. The following are the key findings of the study:

WCB exhibited a reduced viscosity (from 31.62 mm^2/s to 4.69 mm^2/s), a modestly increased calorific value (38,450 kJ/kg), and a safer flash point (89.5°C) compared to diesel. This indicates the improved fuel handling and combustion characteristics. These enhancements make WCB a feasible substitute for diesel in compression ignition engines.

The ternary blends (WCB20Bu10Pr10, WCB20Bu15Pr15, WCB20Bu20Pr20) exhibited favourable rheological behaviour in terms of reduced viscosity, shear stress, and density at elevated temperatures. Among them, WCB20Bu20Pr20 demonstrated the most desirable characteristics that include low viscosity (1.004 mm^2/s at 90°C), minimal shear stress (0.759 Pa), and reduced density (0.771 g/cm^3). This makes it highly suitable for high-speed diesel engine operation under thermal loads.

The thermal stability and flow efficiency of alcohol enhanced biodiesel blends under cold start conditions remain a traditional challenge for biodiesel. The ability to tailor fuel behaviour through alcohol blending offers a valuable strategy for meeting varying engine and climatic demands.

In conclusion, the valorisation of WCO into biodiesel and its analysis through ternary blending presents a compelling pathway for sustainable fuel production. The findings support broader adoption of WCO-based biodiesel in energy policy frameworks within the South African context to promote environmental sustainability, waste valorisation, and energy diversification. Future work should include detailed long-term stability analysis and experimental studies on the engine to assess combustion characteristics, thermal efficiency, and regulated emissions using WCB and its ternary blends. A thorough optimisation analysis across different engine loads and ambient conditions may give the most efficient blend compositions for certain applications. Developing a parallel glycerol upgrading process would support a more integrated biorefinery concept. The life cycle assessment, which includes energy inputs, greenhouse gas emissions, water usage, and waste streams, would provide a quantitative evaluation of the net environmental benefits of WCB-based biodiesel compared to diesel.

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