

Production and Fuel Property Characterization of Biodiesels from Waste Swine Oil and Waste Cooking Oil

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Abstract

Biodiesel fuels were produced from waste swine oil (WSO) and waste cooking oil (WCO) and evaluated in terms of fuel properties, blend characteristics, and purification requirements. The WSO feedstock had an acid value of 0.54 mg KOH/g and an FFA content of 0.27%, indicating low free fatty acidity and allowing direct base-catalyzed transesterification without acid esterification pretreatment, while the higher-FFA WCO required acid esterification. Transesterification was investigated over methanol-to-oil molar ratios of 5:1–12:1 and KOH loadings of 0.5–2.5 wt.%, with 7:1 and 1.0 wt.% KOH selected as the optimum conditions. The biodiesels generally satisfied the evaluated ASTM D6751 requirements. WSO biodiesel contained 96.4 wt.% FAME, marginally below the EN 14214 minimum of 96.5 wt.%, while WCO biodiesel achieved 97.2 wt.%. WSO biodiesel exhibited a cetane number of approximately 65, viscosity of 5.9 mm²/s, density of 886 kg/m³, and cloud point of 14 °C, consistent with its higher saturated FAME content. WCO biodiesel exhibited a cetane number of approximately 54, viscosity of 4.7 mm²/s, density of 880 kg/m³, and improved low-temperature properties, with a cloud point of approximately 2 °C. GC–MS analysis showed that WSO FAMES were predominantly C16:0 and C18:0, while WCO contained higher proportions of C18:1 and C18:2. ULSD blends from B20 to B80 showed improved lubricity, higher flash points, and lower sulfur levels, while calorific value decreased with increasing biodiesel content. These findings demonstrate the viability of WSO and WCO as biodiesel feedstocks, with WSO providing higher ignition quality but requiring more intensive post-reaction purification and washing.

Keywords: Biodiesel, Waste swine oil, Waste cooking oil, Transesterification, Fuel properties, Cetane number, Purification and Waste-to-fuel.

1. Introduction

The depletion of fossil fuels and increasing environmental concerns have led to significant research into renewable biofuels. Biodiesel, which is defined as the Fatty Acid Methyl Ester (FAME) produced through transesterification of organic lipids, has become a popular alternative diesel fuel due to its biodegradability, non-toxicity, and potential for greenhouse gas reduction. Inedible waste oils are particularly attractive feedstocks for biodiesel to avoid competition with food crops and to

reduce production costs. Waste Cooking Oil (WCO), naturally comprising already used vegetable oils from food processing, is produced in large quantities worldwide and offers a low-cost, sustainable feedstock for biodiesel [1]. Using WCO for biofuel aligns with circular economy practices by converting a waste stream into valuable energy [1]. Previous studies have demonstrated the feasibility of high-yield biodiesel from WCO with proper catalyst and process optimization [2]. Waste Swine Oil (WSO), or pork lard from meat processing waste, is a

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comparatively underused feedstock that also shows promise for biodiesel production [3]. Animal fats such as lard are abundant by-products of livestock industries and historically have lower market value than edible vegetable oils [4]. Their use for biodiesel can thus cut raw material costs and address waste disposal issues [4]. Recent studies indicate increasing interest in animal fat waste conversion to biodiesel as part of waste-to-energy and sustainability initiatives [3], [4], [5].

Despite their benefits, waste lipids introduce several practical constraints in biodiesel production. Waste oils often contain elevated free fatty acids (FFAs) and moisture, especially after prolonged storage or repeated thermal exposure [4]. Under alkaline-catalysed transesterification, FFAs react with the base catalyst to form soaps (saponification), which lowers ester yield and complicates phase separation and subsequent purification [4], [6], [7]. WSO, in particular, can exhibit high FFA levels depending on rendering quality and is typically highly saturated, with roughly 39 – 49% saturated fatty acids [4]. This high saturation is associated with favorable combustion-relevant attributes, including a higher cetane number and improved oxidative stability due to the lower degree of unsaturation in the fatty acid methyl ester (FAME) profile. However, the same compositional feature increases melting and crystallization tendencies, resulting in poor low-temperature operability. Biodiesel derived from WSO and similar animal fats commonly exhibits cloud points in the range of approximately 13–16 °C, which can promote gelling or partial solidification even under moderately warm ambient conditions. This established tension between ignition quality and cold-flow performance remains a key constraint for the practical deployment of saturated biodiesel feedstocks, particularly in cooler climates [8], [9], [10], [11]. In contrast, WCO biodiesel is largely derived from unsaturated vegetable oils such as soybean, canola, and palm olein. As a result, its higher proportion of unsaturated FAMES is generally associated with a lower cetane number and reduced oxidative stability when compared with animal fat-derived biodiesel. At the same time, greater unsaturation typically improves low temperature behavior, yielding better cold-flow characteristics (lower cloud and pour points) and improving usability in colder conditions [8], [9]. For example, tallow and lard-derived biodiesels are frequently

characterized by cetane numbers above 60, but cloud points often exceed 10 °C. By comparison, WCO biodiesel derived predominantly from soybean oil commonly reports cetane numbers around 52 – 55 while exhibiting substantially improved cold-flow behavior, with cloud points often below 2.5 °C. Overall, these contrasts highlight the central role of fatty acid saturation in governing ignition quality and crystallization behavior in biodiesel fuels [8], [9], [12]. Numerous studies have documented these feedstock-dependent property differences [13], [14], [15]. In addition, purification is critical for biodiesel produced from waste oils. Crude biodiesel typically contains glycerol, residual catalyst, soaps, and trace contaminants that must be removed through washing or refining to meet fuel quality requirements. Biodiesel produced from animal fats often requires more intensive purification than biodiesel from plant oils [4]. Although conventional water washing is effective, it can generate substantial wastewater on the order of 1 – 3 L per litre of biodiesel [4], [16]. Consequently, alternative dry wash approaches, including adsorption and ion exchange resin systems, as well as other purification strategies, have been explored to reduce wastewater generation and improve process efficiency [17]. In summary, feedstock-specific optimisation of reaction conditions and purification steps is essential to achieve high-quality biodiesel.

Extensive research has examined biodiesel production from a wide range of feedstocks, including virgin vegetable oils and WCO [14], [18], [19]. However, fewer studies provide direct, side-by-side comparisons of animal fat based biodiesel and waste vegetable oil biodiesel produced and evaluated under comparable conditions. The animal fat biodiesel literature, such as tallow and lard, often reports yield or engine behavior in isolation [20], [21], while WCO biodiesel studies are more numerous but frequently remain single-feedstock evaluations. A more integrated understanding of how WSO biodiesel differs from WCO biodiesel across production requirements, fuel properties, and end-use performance remains necessary to guide feedstock-specific process design and engine optimization. In particular, the high FFA and high saturation characteristics of WSO raise practical questions regarding pre-treatment and post-treatment intensity, as well as how blending influences combustion and emissions relative to

the more extensively studied WCO biodiesel. Recent studies assessing WSO biodiesel in compression ignition engines have reported favorable emissions trends, particularly reductions in particulate matter and smoke opacity relative to petroleum diesel, while maintaining acceptable performance. Building on this emerging evidence, the present study advances the field by providing a comprehensive, side-by-side characterization of biodiesels produced from WSO and WCO under comparable production conditions, fuel property measurements, and engine operating regimes [22].

This work responds to identified gaps in biodiesel research, particularly the limited comparative evidence for WSO against WCO-derived biodiesel and the relatively underexplored influence of post-transesterification washing on final fuel quality, an issue highlighted as a priority for future work in recent studies [23]. The study contributes by producing and evaluating biodiesel from both feedstocks under optimized conditions, with specific attention to purification requirements and resulting fuel behavior. The specific contributions are:

- Production and optimization of biodiesel from WSO and WCO, incorporating feedstock-specific transesterification conditions.
- Comprehensive fuel property characterization, including density, kinematic viscosity, acid value, flash point, heating value, cold flow behavior, cetane index, and FAME composition through GC – MS.
- Analysis of post-reaction purification needs, especially the effect of multiple water washings on residual acidity and fuel purity in WSO biodiesel.
- Comparative evaluation of WSO and WCO biodiesel, highlighting physicochemical differences arising from feedstock saturation and their implications for blending, storage, and combustion.
- Assessment of combustion applicability and blending behavior, supporting practical guidance for engine use and policy toward integrating waste-derived biodiesel into the fuel mix.

This structured approach addresses both applied and scientific questions relevant to waste-based biodiesel, including unresolved purification constraints and cold flow limitations in saturated fat biodiesels.

2. Methodology

The methodology outlines the feedstock preparation, transesterification process, post-treatment purification steps, and analytical procedures employed to characterize the physicochemical properties of biodiesel derived from waste swine oil and waste cooking oil.

2.1. Feedstock materials and pre-treatment

WSO and WCO were obtained from local waste streams. The WSO was collected as pork processing waste with visible impurities removed by filtering. The WCO was a blend of used vegetable oils collected from restaurant fryers. Initial characterization of the raw oils included measuring the moisture content by oven drying and the FFA level by titration with potassium hydroxide (KOH). The WSO had an acid value of 0.54 mg KOH/g, and 0.27% FFA, indicating a relatively low free fatty acidity [3], attributable to proper rendering that removed rancid fractions. This low FFA content was within the acceptable range for direct base-catalyzed transesterification [3]. The WCO, however, showed a higher acid value in the range of 5 – 7 mg KOH/g, corresponding to 2.5 – 3.5% FFA due to oil breakdown during cooking. Since FFA greater than 2% can cause excessive soap formation with alkaline catalysts [4], the WCO required an acid esterification pretreatment to reduce FFA before base transesterification.

For WCO, an acid-catalyzed pretreatment was performed. The oil was heated to 55 °C and reacted with methanol at a 0.3 v/v ratio, a 12:1 molar ratio to FFA and 1 wt.% H₂SO₄ as a catalyst in a stirred reactor [6], [7], [24]. After 1 hour, this process esterified the free fatty acids into methyl esters, lowering the acid value of WCO to less than 1 mg KOH/g. The methanol-water phase was decanted, and the pretreated WCO, now “esterified WCO”, was used for the main transesterification step. The WSO feedstock exhibited a low FFA content and therefore did not require an acid esterification pretreatment. The material was instead preheated to approximately 60 °C to ensure complete melting and homogenization, as lard remains semi-solid at ambient temperature [20], [21]. Both feedstocks were dried to <0.1% moisture before reaction, since water can inhibit ester yield and promote soap formation [4], [6], [7], [24].

2.2. Transesterification process

Transesterification of both oils was carried out in batch mode. A methanol-to-oil molar ratio of 6:1 was initially employed as the baseline condition based on established transesterification procedures [25], [26], [27]. For process optimization, however, the experimental matrix was extended over methanol-to-oil molar ratios of 5:1–12:1 and KOH catalyst loadings of 0.5–2.5 wt.%. These ranges were selected to evaluate the effects of both insufficient and excess methanol and catalyst on biodiesel yield and phase separation. The experimental results identified a methanol-to-oil molar ratio of 7:1 and a KOH concentration of 1.0 wt.% as the selected optimum, providing a favorable balance between biodiesel yield, reaction efficiency, and subsequent phase separation. At higher methanol ratios, particularly toward 12:1, effective product recovery decreased because excess methanol increased glycerol solubility in the ester phase, while excessive catalyst loading promoted soap formation and complicated phase separation. For each reaction, 1 L of oil was loaded in a 2 L glass reactor equipped with mechanical stirring at 600 rpm and temperature control. An alkaline catalyst - potassium hydroxide (KOH) was chosen for its fast reaction rate and cost-effectiveness [28], [29], [30]. The catalyst amount was 1 wt.% of oil for WSO and 0.8 wt.% for pre-treated WCO, this is slightly lower for WCO given its lower viscosity and the prior acid step. KOH was dissolved in methanol to form potassium methoxide in situ. The methanolic KOH solution was added to the heated oil, and the transesterification reaction proceeded at 60 °C for 1.5 hours. Samples were taken to monitor reaction progress. The conversion of triglycerides to methyl esters was tracked by thin-layer

chromatography (TLC) and later verified by Gas Chromatography – Mass Spectrometry (GC–MS) analysis of the product.

Both WSO and WCO exhibited efficient conversion under these conditions. The base-catalyzed reaction is known to achieve more than 90%–95% ester yield within 1 hour for low FFA oils [4]. In this experimental study, WSO reached 93% conversion after 1 hour and 97% after 2 hours, while the esterified WCO reached 95% conversion within 1 h. The slightly faster conversion of WCO can be attributed to its lower viscosity and more homogeneous phase mixing, while the more saturated WSO with initial solid fat formed a thicker phase that took longer to be fully converted. However, both feedstocks attained high conversion efficiencies comparable to refined vegetable oils, consistent with literature reports for optimized conditions [18], [19], [31]. The use of an alkaline catalyst provided much faster reaction kinetics than acid catalysts, which would require 10× longer [4], [30], [32], [33].

After reaction, the mixture was allowed to settle, separating into two phases for at least 4 hours at 50 °C. Glycerol, along with catalyst residues and soaps, settled as a dense lower phase, which was then drained as shown in Figure 1 (a) and (b). Approximately 10% glycerol by-product by volume of oil was recovered, consistent with the stoichiometric expectation of 1 kg glycerol per 10 kg biodiesel produced [34], [35]. The crude upper phase was raw biodiesel containing FAMES as well as residual impurities such as methanol, soap, catalyst, traces of mono- and di-glycerides. This raw biodiesel was subjected to purification as described next.

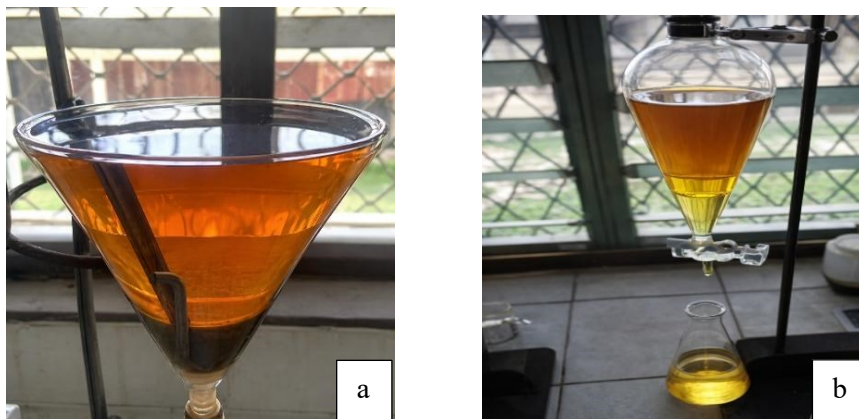


Figure 1. (a) WCO biodiesel; (b) WSO biodiesel.

2.3. Biodiesel purification and multiple washing

For the WCO biodiesel, purification was relatively straightforward. The crude methyl esters were first heated to 70 °C to evaporate most of the remaining methanol. The biodiesel was then washed with warm deionized water between 50 – 60 °C at 10% volume of biodiesel, gently mixed, and allowed to separate. Two wash cycles were sufficient for WCO biodiesel to reach neutral pH and a clear appearance. The wash water was initially milky due to residual soap and catalyst removal but became clear by the second wash. Finally, the washed biodiesel was dried by heating to 110 °C under vacuum to remove moisture. The resulting WCO biodiesel was clear, golden-colored, and met American Society for Testing and Materials (ASTM) standards for water content of less than 500 ppm and sediment.

Purifying the WSO biodiesel required more intensive washing. Owing to its animal-fat origin, the crude WSO biodiesel contained higher soap levels with potassium soaps of fatty acids from any residual FFA neutralization. These soaps, along with a catalyst, made the first wash water strongly basic at a pH greater than 9 and turbid. Warm water at 60 °C was used to prevent the FAME from solidifying during washing since lard FAME has a high melting point [3], [36]. The biodiesel was washed in successive stages. About 5% hot water was added, the mixture was gently agitated, then allowed to settle until phase separation. The spent wash water was drained, and the process was repeated with fresh hot water. Multiple

wash cycles, typically 3 – 5 cycles, were needed until the wash water was neutral at pH 7 and no soap foaming was observed. This stepwise washing removed residual KOH and soap effectively [3]. After washing, the WSO biodiesel was vacuum dried at 80 °C for 1 hour.

The final purified WSO biodiesel was clear and light yellow. Notably, it solidified into a soft fat at room temperature of 23 °C, confirming its high saturation. It was stored at 50 °C to remain liquid until testing. Despite the extra effort of more wash water and heat required for WSO biodiesel, the purification was successful. The acid value dropped to less than 0.25 mg KOH/g and free glycerol to less than 0.02%, meeting fuel specifications [4]. It was noted that alternative purification methods, such as dry wash using magnesium silicate or ion-exchange resin, were considered to reduce wastewater generation [17], and could be applied in future to WSO biodiesel to streamline purification. Figure 2 summarizes the production process in a diagram.

2.4. Fuel physicochemical characterization and energy basis for performance metrics

The fuel properties used in the present study were determined from direct laboratory measurements of the same waste swine oil biodiesel and waste cooking oil (B100) batch produced by this study. The batch-specific physicochemical characteristics are summarized in Table 1.

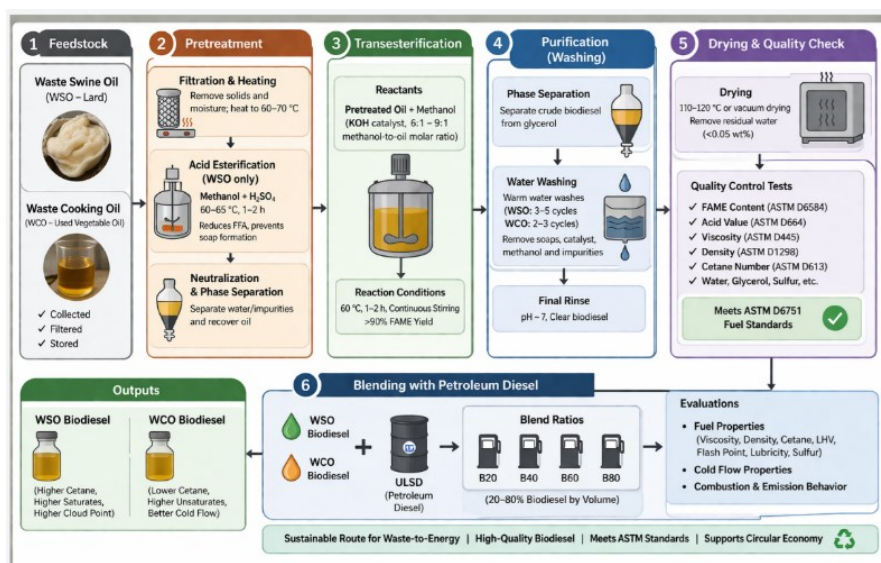


Figure 2. Schematic diagram of biodiesel production from WSO and WCO.

Table 1. Fuel properties of petroleum diesel, WSO biodiesel, and WCO biodiesel after purification, compared to ASTM D6751 limits.

Property	Unit	Petroleum Diesel	WSO Biodiesel	WCO Biodiesel	ASTM Limit	D6751
Kinematic Viscosity @ 40 °C	mm ² /s	2.5	5.9	4.7	1.9 – 6.0	
Density @ 15 °C	kg/m ³	820	886	880	—	
Acid Value	mg KOH/g	0.01	0.23	0.15	≤ 0.50	
Cloud Point	°C	-7	14	2	—	
Flash Point	°C	58	156	173	≥ 130	
Cetane Number	—	48.7	65	54	≥ 47	
Water Content	wt. %	0.005	0.015	0.01	≤ 0.05	
Free Glycerol	wt. %		0.012	0.005	≤ 0.02	
Total Glycerol	wt. %	0	0.23	0.18	≤ 0.24	
Sulfated Ash	wt. %	< 0.001	0.012	0.009	≤ 0.02	
Phosphorus Content	ppm	< 1	7	5	≤ 10	
FAME Content	wt. %	0	96.4	97.2	≥ 96.5	

2.4.1. Density at 15 °C (ASTM D4052)

Density was measured at 15 °C using an oscillating U-tube digital density meter (Anton Paar DMA 5000, Anton Paar GmbH, Graz, Austria), in accordance with ASTM D4052 [37], within the instrument operating range of approximately 0–3 g cm⁻³ and 0–90 °C. The method used is based on introducing a small aliquot of sample into a temperature-controlled oscillating tube and computing density from the oscillation response after thermal equilibrium is attained. Initial calibration and recalibration after any change in test temperature were performed by reconditioning the measuring cell and determining the instrument constants from measurements with dry air and freshly boiled and cooled reagent water. The cell was cleaned with a volatile solvent, dried with dry air, and conditioned to minimize carryover, followed by air adjustment (dry air) and water adjustment (reagent water). Instrument performance at the measurement temperature was verified using a single n-nonane check, and results were accepted when the measured value met the laboratory control limit of ± 0.00010 g cm⁻³ relative to the n-nonane reference value at 15 °C. The verification outcome and instrument constants were documented and reviewed against acceptance criteria before reporting sample density values.

2.4.2. Kinematic viscosity at 40 °C (ASTM D445)

Kinematic viscosity was measured at 40 °C using an automated calibrated capillary viscometry system (CANNON CAV 4.1, CANNON Instrument Company, State College, Pennsylvania, USA), in accordance with ASTM D445 [38]. Each sample was equilibrated at 40 °C, and the efflux time required for a fixed volume to flow under gravity between two timing marks in a calibrated capillary was recorded. Kinematic viscosity was calculated as the product of the measured efflux time and the applicable viscometer constant, and two determinations were performed per sample to obtain the reported value. The viscometry bath was maintained under strict thermal control to ensure a stable test temperature consistent with high precision practice. System calibration and verification were conducted daily and repeated after any capillary replacement or cleaning by confirming and stabilizing bath temperature using a calibrated reference thermometer, verifying viscometer constants against current capillary calibration certificates, and measuring a certified viscosity reference oil at 40 °C to confirm agreement with the certified value. Following cleaning, a post-cleaning blank timing check was performed using n-heptane as the solvent to verify the absence of residual contamination before accepting and reporting the sample results.

2.4.3. Flash point (ASTM D93)

Flash point was determined using an automatic Pensky–Martens closed-cup apparatus (Koehler K16270, Koehler Instrument Company, Holtsville, New York, USA) in accordance with ASTM D93 [39], Procedure C (automated method for biodiesel). The sample was charged into the closed cup and heated under continuous stirring. An initial approach heating phase was used to bring the sample to the test region, defined as the temperature range starting at approximately 24 °C below the expected flash point, after which heating proceeded at 2.5–3.5 °C min⁻¹. The ignition source was applied automatically at defined temperature intervals within this region, commencing at the test region start point and subsequently at 2 °C increments until a transient flash was detected. The corresponding temperature was recorded as the flash point. Laboratory quality control included documented pre-run checks of cup and lid cleanliness, ignitor/shutter function, stirring performance, and verification of the temperature measurement system against a traceable reference. Method performance was monitored through periodic analysis of a Pensky–Martens-certified reference material and reviewed against laboratory control limits. Additional checks were conducted weekly after servicing and when drift was suspected, including confirmation of the programmed heating rate and ignition interval settings, functional checks of ignition and detection response, and repeat CRM analysis. Barometric pressure correction was applied in accordance with ASTM D93 and the instrument algorithm before reporting results.

2.4.4. Higher heating value (ASTM D240)

Higher heating value, or the gross heat of combustion, was determined by oxygen bomb calorimetry using a Parr 6200 calorimeter (Parr Instrument Company, Moline, Illinois, USA) in accordance with ASTM D240 [40] under controlled laboratory temperature conditions. A nominal 1.0 g test portion of biodiesel was used, with the mass controlled to produce a temperature rise equivalent to that obtained from combustion of 0.9–1.1 g benzoic acid as required by ASTM D240. The test portion mass was recorded to the nearest 0.1 mg before combustion. The sample was combusted completely in excess oxygen within a sealed bomb immersed in the calorimeter vessel,

and the Higher Heating Value (HHV) was calculated from the corrected temperature rise in the calorimeter system and the calibrated calorimeter energy equivalent. The calorimeter energy equivalent (W) was established by standardization with benzoic acid, performing at least six standard combustions over a minimum of three days using charge masses of 0.9–1.1 g. For each standardization burn, the corrected temperature rise (ΔT) and corresponding “W” were calculated, applying the prescribed corrections for ignition wire consumption and nitric acid formation. The calorimeter was re-standardized following maintenance, bomb replacement, or any indication of control drift. On each analytical day, a benzoic acid verification burn was performed at the start of the run to confirm instrument readiness before sample measurements. For brake thermal efficiency (BTE) calculations, the Lower Heating Value (LHV) was used as the energy basis and was derived from the measured HHV by accounting for the latent heat of vaporization of water formed during combustion.

2.4.5. Cetane index (ASTM D6890)

Ignition quality testing was performed on B100 WSO for the determination of Derived Cetane Number (DCN), in accordance with ASTM D6890 [41], using an Ignition Quality Tester (IQT–D6890-type constant volume chamber, CFR Engines (IQT Product Line), Ottawa, ON, Canada) operated as a closed combustion chamber system under controlled charge and temperature conditions [41], [42]. The IQT platform (laboratory rig) was operated with synchronized control and data acquisition implemented on a National Instruments Compact RIO real-time controller (NI CompactRIO-9012, NI National Instrument, Austin, TX, USA) with an NI 9112 eight-slot FPGA chassis (NI National Instrument, Austin, TX, USA). Temperature acquisition was implemented using K-type thermocouples connected to an NI 9213 thermocouple input module (NI National Instrument, Austin, TX, USA), while quasi-static analog acquisition for supporting channels, including charge pressure and injector actuation-related pressure, was implemented using an NI 9215 module (NI National Instrument, Austin, TX, USA). Combustion pressure, which provided the primary signal for ignition delay determination and DCN calculation, was measured using a Kistler 6121 piezoelectric pressure transducer (Kistler Group,

Winterthur, Switzerland) mounted in a water-cooled tee arrangement. Optical and timing diagnostics were available as supporting checks, including ignition/flame luminosity detection using a Honeywell 5620 Optoschmitt detector (Honeywell, Charlotte, NC, USA) installed in the optical fitting and injection/spray timing confirmation using a diode laser-phototransistor arrangement comprising a Quarton VLM 635-01 LPA diode laser module (QUARTON Inc, New Taipei City, Xizhi District, Taiwan) and an Optek 803 SL phototransistor receiver (TT Electronics (Optek Technologies Brand, Woking, United Kingdom).

Before each test session, the coolant system was energized through an uninterrupted power supply, and coolant circulation was confirmed using the instrument flow indicator. The chamber wall/surface temperature was set to the method set point and allowed to stabilize before injections commenced. System integrity was verified using a pre-test leak rate gate check. The exhaust valve was closed, the chamber was charged to the standard operating pressure, the intake valve was then closed to isolate the vessel, and pressure decay was monitored for 20 s with the charge amplifier in DC-Long mode. Testing proceeded only when the leak rate met the laboratory acceptance criterion of less than 3.5 kPa s⁻¹ from an initial pressure of 21.37 bar, ensuring stable charge conditions during ignition delay acquisition.

Calibration and ongoing readiness control were implemented using n-heptane as the ASTM D6890 calibration reference material, with the n-heptane check performed at the start of each analytical day and repeated after any interruption, servicing activity, or indication of drift. The temperature setting was adjusted as required to reproduce the assigned ignition delay target (ID_ARV) of 3.78 ms. This n-heptane activity was applied as a commissioning and quality-control gate and was not treated as part of the biodiesel experimental matrix. Following successful n-heptane calibration, the biodiesel testing was conducted without multi-fuel switching, and the fuel system was conditioned with the same biodiesel before data acquisition to ensure stable delivery and repeatable injections. A short preliminary automated sequence was executed at the start of each session to confirm subsystem operation and optical alignment before the main test sequence was initiated. During testing, chamber charge conditions and temperature were

maintained at their set points by the instrument regulators and control system, and results were accepted only when logged operating conditions remained within laboratory stability limits and ignition delay signals were repeatable across replicate injections. Measurement chain verification was performed for temperature and pressure channels. The thermocouple acquisition chain was verified using a Fluke 741B process calibrator (Fluke Corporation, Everett, WA, USA) configured to simulate K-type thermocouple outputs at defined temperatures. Pressure channel verification was performed using a Druck DPI 620 pressure calibrator (Druck (Baker Hughes), Leicester, United Kingdom) to confirm pressure signal conversion relationships used for monitoring charge conditions and for uncertainty assessment.

2.4.6. Acid value (ASTM D664)

Acid value was determined by non-aqueous potentiometric titration in accordance with ASTM D664 [43]. Test Method A was used and reported as milligrams of potassium hydroxide per gram of sample (mg KOH g⁻¹), representing the amount of base required to neutralize acidic constituents in the fuel. The biodiesel sample test portion of approximately 10.0 g was dissolved in the ASTM D664 titration solvent composed of toluene, propan-2-ol, and water = 500:495:5 (mL per liter). The solution was titrated with 0.1 mol L⁻¹ KOH in an alcoholic medium while monitoring electrode potential to obtain a potentiometric endpoint, thereby improving endpoint objectivity and repeatability. The KOH titrant normality was standardized against potassium hydrogen phthalate (KHP) as a primary standard, and titrant concentration control documentation was maintained. A solvent blank was analyzed routinely and applied as a correction to sample results, and an acid number check standard with oil-certified reference material was analyzed at least weekly to verify ongoing method performance. Electrode conditioning, cleaning, and storage were performed in accordance with the laboratory standard operating procedure to maintain a stable potentiometric response before reporting final acid value results.

2.4.7. Free and total glycerol (ASTM D6584)

Free and total glycerol were quantified using gas chromatography after derivatization, in alignment with

ASTM D6584 [44], on a gas chromatography–mass spectrometer (Agilent 7890–5975C, Agilent Technologies, Santa Clara, CA, USA). The method is based on converting polar glycerol and glyceride species into more volatile derivatives to enable reliable chromatographic separation and quantification. Accordingly, samples and calibration solutions were derivatized by silylation with N-methyl-N-(trimethylsilyl) trifluoroacetamide (MSTFA) under fixed time–temperature conditions specified in the laboratory standard operating procedure. Following MSTFA addition, the derivatization mixture was maintained at room temperature, approximately 20–25 °C, for 20 min to complete silylation, after which the derivatized solution was diluted as required and analyzed by GC. Quantification was performed using an internal standard approach and multi-component calibration to determine free-glycerol and bound-glycerol species of mono-, di-, and triglycerides, which were subsequently expressed on an equivalent glycerol basis as required by the method.

For each analytical batch, a five-level calibration series was prepared using internal standards, and calibration acceptance was based on meeting the laboratory linearity criterion of r^2 threshold and fit-for-purpose response performance. A solvent blank was analyzed to confirm the absence of carryover before sample injections, and continuing calibration verification standards were injected periodically throughout the sequence to confirm calibration stability. Retention time consistency and chromatographic performance were checked using the calibration/standard mixture for glyceride species, and instrument response stability was monitored across the run to ensure reliable identification and quantification before reporting final free and total glycerol results.

2.4.8. FAME content (EN 14103)

FAME content was quantified directly on the finished biodiesel by gas chromatography in accordance with European Standard (EN) 14103 [45], using a Shimadzu GC-2014 system (Shimadzu Corporation, Kyoto, Japan) operated with a temperature program suitable for resolving the biodiesel methyl ester envelope [45], [46]

The method was based on an internal standard quantification approach using methyl nonadecanoate (C19:0) to support robust ester-content determination for

WSO biodiesel. An internal standard solution of methyl nonadecanoate (C19:0) was prepared in GC-grade n-heptane at 10 mg mL⁻¹, and a fixed volume (1.00 mL) of this internal standard solution was added to each weighed biodiesel test portion before GC analysis. Total ester content was then calculated from the integrated FAME peak region relative to the internal standard response under identical chromatographic conditions. The instrument was conditioned to achieve a stable baseline and consistent retention-time performance at the programmed operating conditions. Calibration was established for each analytical batch by preparing a multi-level internal standard calibration series in accordance with EN 14103, ensuring that each calibration level contained the internal standard at the same concentration used for sample preparations. The calibration curve was accepted only after meeting the laboratory's linearity acceptance criteria and demonstrating consistent internal standard response across the calibration range. Chromatographic resolution and retention order were verified using a certified FAME mixture to confirm adequate separation across the ester region and to validate peak identification boundaries for integration. A biodiesel quality control material was analyzed within the batch to confirm method performance under routine conditions, and results were accepted only when the QC outcome satisfied laboratory control limits.

Each biodiesel specimen was homogenized, combined with the internal standard, and injected under the same GC conditions used for calibration. Ester content was calculated by integrating the defined FAME peak region and applying the EN 14103 internal standard calculation, with batch calibration used to convert response ratios to ester content. Sequence integrity was maintained by monitoring internal standard area stability and retention time consistency throughout the run, and any deviation from control limits triggered corrective action and repeat analysis before the final results were released.

Additionally, GC–MS analysis was performed on the methyl esters to determine their fatty acid methyl ester profile. A capillary GC with MS detection identified the FAME components by comparing retention times to standards. This provided the composition, such as % methyl palmitate C16:0, methyl stearate C18:0, methyl oleate C18:1, etc., which is useful for explaining the observed fuel properties [20], [21], [47].

2.5. Data analysis and modeling

All measurements were conducted in duplicate, with values expressed as averages. Where applicable, measurement uncertainty ($\pm$) is specified. Fuel properties were benchmarked against ASTM D6751 and EN 14214 biodiesel specifications. For the analysis of blend behavior, regression models were employed to examine the relationship between biodiesel volume fraction and fuel properties. Linear regression was suitable for variables such as density and kinematic viscosity, which exhibited strong linear dependence on blend ratio ($R^2 > 0.99$ for both WSO and WCO biodiesels). In contrast, second-order polynomial regressions were applied to properties exhibiting mild nonlinear behavior, including flash point and calorific value. Regression coefficients were evaluated for statistical significance and predictive reliability.

To assess biodiesel yield optimization, a two-variable empirical model was developed using methanol-to-oil molar ratio and potassium hydroxide (KOH) catalyst concentration as the design factors. The response surface methodology (RSM) was applied to interpret trends and locate optimal operating conditions. Experiments were conducted across a design matrix comprising methanol-to-oil molar ratios of 5:1–12:1 and KOH catalyst loadings of 0.5–2.5 wt.%. The resulting biodiesel yield data were fitted using a second-order polynomial function, as shown in Equation (1):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{12} X_1 X_2 \quad (1)$$

where Y is the FAME yield, X1 is the methanol-to-oil molar ratio, and X2 is the catalyst concentration.

The yield map derived from this model was used to picture the yield landscape and delineate suboptimal regions (yield < 90%) due to either insufficient reactants or detrimental side effects such as soap formation and poor phase separation. The responses of WSO and WCO were generally comparable within the investigated design space, although feedstock-dependent differences in catalyst sensitivity were observed.

The following boundary conditions and assumptions were applied in the modeling:

- Isothermal conditions were assumed during reaction (approximately 60 °C), as temperature was maintained constant in all trials.
- Complete mixing and homogeneity were presumed based on the use of vigorous magnetic stirring throughout transesterification
- Reaction time and post-treatment protocols were held constant to isolate the effects of methanol and catalyst concentration.
- No kinetic or thermodynamic modeling was conducted beyond the empirical response surface fitting.

This combined approach of empirical modeling and regression analysis supports quantitative interpretation of biodiesel production parameters and facilitates direct comparison with previous studies on transesterification optimization and emissions [9], [48], [49]. A summary of experimental conditions and process variables is provided in Table 2. The subsequent section presents the results, including detailed tables and figures of fuel properties and blend performance indicators.

Table 2. Summary of baseline biodiesel production and purification conditions for WSO and WCO feedstocks.

Parameter	Waste Swine Oil (WSO)	Waste Cooking Oil (WCO)
Feedstock Pre-treatment	Filtration, Preheating/melting, and drying	Filtration, heating, and acid esterification
Catalyst Type	KOH (Potassium Hydroxide)	KOH (Potassium Hydroxide)
Catalyst Concentration (wt.%)	1.0	0.8
Methanol-to-Oil Molar Ratio	6:1	6:1
Reaction Temperature (°C)	60	60
Reaction Time (min)	90	90
Stirring Speed (rpm)	600	600
Number of Washings	3 - 5	2
Washing Medium	Warm distilled/deionized water (60 °C)	Warm distilled/deionized water (50-60 °C)
Settling Time (per washing, min)	30	30
Mass Biodiesel Yield (%)	90	93

Table 3. Summary of fuel properties.

Fuel Type	Density (kg/m ³)	Viscosity (mm ² /s)	Cetane Number	Flash (°C)	Point Cloud (°C)	Point LHV (MJ/kg)	Lubricity (μm)
ULSD	820	2.87	48.7	58	-7	45.5	520
B20 (WSO)	843	3.31	52	85	5	43.93	300
B80 (WSO)	872	4.9	63	103	8	39.23	200
B100 (WSO)	886	5.9	65	156	14	37.66	180
B20 (WCO)	839	3.23	50	89	-6	43.77	300
B80 (WCO)	863	4.5	55	160	-	38.59	200
B100 (WCO)	880	4.7	54	173	2	36.86	180

The values presented in Table 2 represent the baseline feedstock-specific production conditions. For process optimization, methanol-to-oil molar ratio and KOH concentration were systematically varied over 5:1–12:1 and 0.5–2.5 wt.%, respectively, as described in the response-surface analysis.

3. Results

A comprehensive fuel test was conducted on the purified biodiesels and their blends with petroleum diesel. Blends of 20%, 40%, 60%, and 80% biodiesel by volume, denoted B20, B40, B60, and B80, were prepared for each biodiesel type using Ultra-Low Sulfur Diesel (ULSD) as the base fuel. Key properties were measured according to ASTM standard test methods. The results are presented in Table 3, and the analysis includes the physicochemical properties, production efficiencies, and washing characteristics of biodiesel synthesized from waste swine oil and waste cooking oil under defined transesterification conditions.

3.1. Biodiesel production yields and purity

Biodiesel production yields and purity levels were assessed to evaluate the conversion efficiency and effectiveness of post-reaction purification for both WSO and WCO feedstocks. The transesterification process was optimized through a series of experimental trials in which the methanol-to-oil molar ratio was systematically varied from 5:1 to 12:1 and the KOH catalyst loading from 0.5 to 2.5 wt.%. Yields were found to be strongly influenced by both parameters. The optimal condition of 7:1 molar ratio and 1.0 wt.% KOH provided a balance between high

conversion and phase-separation efficiency while minimizing soap formation and methanol-induced glycerol solubility.

3.1.1. Transesterification yield

Both feedstocks yielded high biodiesel conversion under the optimized conditions. Biodiesel yield was evaluated using volumetric recovery. The FAME content of the final purified biodiesels, determined by GC analysis in accordance with EN 14103, was 96.4 wt.% for WSO and 97.2 wt.% for WCO. The WCO biodiesel therefore satisfied the minimum ester-content requirement of 96.5 wt.% specified by EN 14214, while the WSO biodiesel was marginally below this threshold by 0.1% point. This small deviation indicates that, although the WSO biodiesel achieved a high degree of ester conversion, it did not fully satisfy the EN 14214 ester-content criterion under the experimental conditions employed. The small remainder consists of mono and diglycerides, which were slightly higher in WSO biodiesel with a total glycerol of 0.23% against 0.18% in WCO, which is likely due to the higher viscosity slowing mass transfer [4]. The volumetric yield of biodiesel per unit oil was approximately 0.98 L biodiesel per L of WCO and 0.96 L per L of WSO at 15 °C, accounting for density differences. On a mass basis, the yield from WSO was 90%, slightly lower than the 93% observed for WCO, due to greater soap formation and loss during purification. Within the investigated design space of 5:1–12:1 methanol-to-oil molar ratio and 0.5–2.5 wt.% KOH, the highest overall process performance was observed around the selected optimum condition. The maximum biodiesel yield attained at a methanol-to-oil molar ratio of 7:1 reflects the relationship

between chemical equilibrium and physical separation dynamics. While increasing methanol content initially favors forward transesterification by shifting the equilibrium toward fatty acid methyl ester (FAME) formation, yields decline beyond a 7:1 ratio due to adverse effects on product separation. Specifically, excess methanol enhances the solubility of glycerol in the methyl ester layer, disrupting clear phase separation and promoting glycerol entrainment in the biodiesel phase, which reduces effective recovery. This behavior is validated in the biodiesel literature, where methanol excess beyond optimal levels has been shown to impair phase clarity and decrease general conversion efficiency [18], [31], [50]. Accordingly, the 7:1 molar ratio emerges as a practical optimum, ensuring high FAME yield while preserving effective phase separation and downstream recovery. These yield values are consistent with other studies using similar feedstocks. Encinar, et al. [51] reported 94% yield for lard through two-step catalysis, and yields of 95 – 97% are common for waste oils after pretreatment [31], [48], [52].

The final biodiesels were clear of any visible glycerol or soap residues after the applied purification. The acid values were reduced to 0.23 mg KOH/g for WSO biodiesel and 0.15 mg KOH/g for WCO biodiesel, both well below the ASTM D6751 specification limit of 0.50 mg KOH/g, indicating negligible residual free fatty acid content [4]. The WSO feedstock had an initial acid value of 0.54 mg KOH/g, corresponding to 0.27% FFA, and therefore did not require acid esterification before base-catalyzed transesterification.

Following transesterification, the WSO biodiesel required 3–5 sequential warm-water washing cycles to remove residual catalyst, soaps, and other impurities, while WCO biodiesel required 2 washing cycles. The effectiveness of the washing was also confirmed qualitatively by the disappearance of emulsion in the final rinse. After drying, the residual water content was below 0.05 wt.% for WSO biodiesel and below 0.02 wt.% for WCO biodiesel, fully complying with ASTM limits for moisture content. The influence of the methanol-to-oil ratio and KOH catalyst on biodiesel yield is shown in Figure 3, where yield trends are plotted across varying transesterification conditions, which highlights the sensitivity of the reaction to these parameters and confirming the optimal yield point.

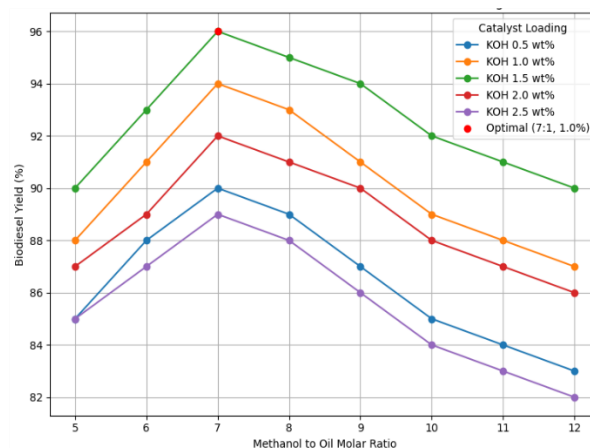


Figure 3. Biodiesel yield versus methanol-to-oil molar ratio at different KOH catalyst loadings of 0.5–2.5 wt.%

3.1.2. Fatty acid methyl ester composition

The reaction parameters, particularly temperature and residence time, were held constant across all experimental batches to isolate feedstock-dependent effects. Accordingly, the objective was not to modify the fatty acid methyl ester distribution, but rather to ensure complete transesterification while preserving the inherent fatty acid profile of each feedstock. GC – MS analysis indicated a distinct FAME composition for the WSO biodiesel. The fuel was primarily composed of 32% methyl palmitate C16:0, 18% methyl stearate C18:0, 41% methyl oleate C18:1, and 7% methyl linoleate C18:2, with minor contributions from methyl myristate (C14:0, 1%) and methyl linolenate (C18:3, <1%). The profile comprised approximately 50% saturated, 41% monounsaturated, and 7 – 8% polyunsaturated FAMES, which is consistent with the characteristic fatty acid distribution reported for pork lard-derived biodiesel [4], [21], [53], [54] where lard commonly contains 25 – 30% palmitic, 12 – 15% stearic, 40 – 45% oleic, and 10 – 15% linoleic [4]. In contrast, WCO biodiesel, derived from mixed household cooking residues, displayed greater unsaturation: approximately 22% C16:0, 6% C18:0, 46% C18:1, 24% C18:2, and 1 – 2% C18:3, with traces of longer and shorter-chain FAMES. Consequently, the WCO FAME had 30% saturates as against 50% for WSO, and 25% polyunsaturates against less than 10% for WSO. These compositional differences reinforce the observed variations in cold flow, density, and combustion behavior between the two fuels [21], [47], as discussed below. The molecular weight distribution was similar, with a mean

molecular weight of 290 g/mol for WCO FAME against 292 for WSO FAME, implying similar energy content per unit mass and comparable stoichiometric air–fuel ratios.

3.1.3. Purity and contaminants

The total glycerol content, comprising both free and bound glycerin fractions, was measured to assess transesterification completeness and residual contamination. Post-transesterification purification was performed using sequential warm-water washing, with the number of washing cycles determined by feedstock-specific purification requirements. WSO biodiesel required 3–5 washing cycles, while WCO biodiesel required two cycles. Purification effectiveness was assessed from residual soap/emulsion formation, acid value, glycerol content, moisture, and ash content. The WSO biodiesel exhibited a total glycerol concentration of approximately 0.23 wt.%, with free glycerol accounting for about 0.012 wt.% and the remaining fraction attributed to mono and diglycerides. In comparison, the WCO biodiesel presented a lower total glycerol content of approximately 0.18 wt.%, with free glycerol measured at about 0.005 wt.%. Both are under the EN 14214 limit of 0.25%. The ash content with residual inorganic content from catalyst or salts was less than 0.005% for both, and no measurable sulfated ash was detected, indicating effective removal of catalyst and soap [48]. Elemental analysis showed that both biodiesels contain 10.8 – 11.0% oxygen by mass, consistent with nearly pure FAME, while diesel fuel contains 0% oxygen. No sulfur was detected in either biodiesel, with less than 5 ppm, against 11 ppm in the ULSD used for blending. This essentially sulfur-free nature of biodiesel is a known benefit for emissions reduction, which also is SO₂ elimination [1].

The final purified biodiesels exhibited FAME contents of 96.4 wt.% for WSO and 97.2 wt.% for WCO, as determined by GC analysis in accordance with EN 14103. WCO satisfied the EN 14214 minimum ester-content requirement of 96.5 wt.%, while WSO was marginally below the threshold by 0.1 percentage point. However, the high FAME content of WSO demonstrates substantial ester conversion, although further process optimization would be required to achieve full compliance with the EN 14214 ester-content criterion.

3.2. Fuel properties of WSO and WCO biodiesel

The neat biodiesel fuels (B100) from WSO and WCO were first examined. Table 1 summarizes the key fuel properties measured for each, alongside reference diesel fuel values and standard limits.

3.2.1. Density

WSO biodiesel had a density of 0.886 g/cm³ at 15 °C, higher than WCO biodiesel at 0.880 g/cm³, and higher than diesel at 0.820 g/cm³. This is typical, as biodiesel densities often range from 0.86 to 0.90 due to the presence of oxygenated ester groups. The higher density of WSO biodiesel correlates with its higher fraction of saturated long-chain FAME, which pack more tightly. Both densities fall within the range specified by standards of 0.86 – 0.90 g/cm³ for EN 14214 and indicate that, in volumetric terms, a liter of WSO biodiesel contains slightly more mass and hence more moles of fuel than a liter of WCO biodiesel [23], [55].

3.2.2. Viscosity

At 40 °C, WSO biodiesel's kinematic viscosity was 5.91 mm²/s, whereas WCO biodiesel was 4.69 mm²/s [2]. Both are within ASTM D6751's allowance of 1.9 – 6.0 mm²/s, though WSO is near the upper end [2]. The higher viscosity of WSO biodiesel is attributed to its saturated FAME, such as methyl stearate, which is more viscous than methyl linoleate. The result implies that pure WSO biodiesel will have slightly poorer fuel atomization than WCO biodiesel, but it remains manageable in diesel engines, especially at fuel temperatures of 60 – 90 °C in modern common-rail systems. Notably, blending with diesel significantly reduces viscosity, even a 20% blend of WSO biodiesel (B20) had a viscosity of 3.3 mm²/s, only 15% above pure diesel's 2.87 mm²/s, as shown in Figure 4 (a) and (b). WSO biodiesel yields slightly higher density and significantly higher viscosity at a given blend ratio due to its greater saturation and longer carbon chains. Blending with petroleum diesel reduces the viscosity approximately linearly, bringing even B80 within the acceptable range of less than 5.5 mm²/s. Density shows a near-linear increase with biodiesel content. The deviation from linearity for WSO blends is minor, indicating ideal volumetric blending behavior.

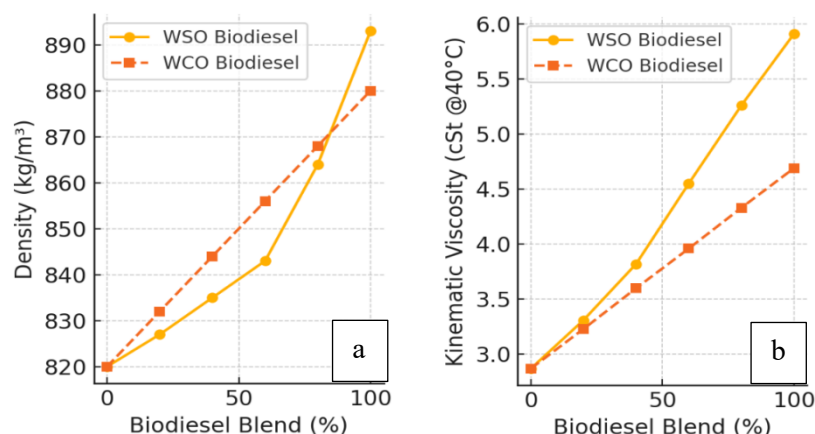


Figure 4. Variation of: (a) density against biodiesels; (b) kinematic viscosity (at 40 °C) with biodiesel blend of WCO and WSO against WCO biodiesels.

3.2.3. Flash point

The flash point of WSO biodiesel was measured at 156 °C on the Pensky-Martens closed cup, whereas WCO biodiesel exhibited a flash point of 173 °C on average [3], [56]. Both far exceed the minimum flash point for safety, which is 93 °C per ASTM D6751. The high flash points confirm that virtually all residual methanol was removed by the washing/drying, biodiesel's flash point is primarily determined by any trace alcohol.

The slightly lower flash of WSO biodiesel at 156 °C suggests it may have retained a small amount of residual methanol or lighter compounds, or it could be an intrinsic difference of some unsaturated in WCO, which may have slightly higher flash. In any case, these values ensure that both biodiesels are very safe to handle compared to diesel fuel, which had a flash point of 58 °C in our tests, typical for ULSD. When blending, the flash point of the mixture is dominated by the volatile component of diesel. B20 blends of WSO and WCO biodiesel had flash points of 85 °C and 89 °C, respectively, substantially higher than neat diesel but below 100 °C. At B80, flash points were 103 °C for WSO and 160 °C for WCO. Notably, WCO B80 already exceeds 150 °C, because WCO B100 itself was extremely high, which might be due to less residual methanol than WSO B100.

Figure 5 (a) illustrates flash point rising with biodiesel content. The non-linearity is evident. WCO biodiesel, having a very high flash, causes a sharp increase even at moderate blend ratios, while WSO biodiesel's effect is a bit more modest due to its slightly lower B100 flash.

However, even B20 blends of both types have flash points 30 °C higher than diesel, improving fuel safety for storage and transport.

3.2.4. Cetane number

The derived cetane number (DCN) for WSO biodiesel was 65, measured CN = 64 – 65, while for WCO biodiesel it was 54, measured CN = 53 – 55 [1]. This marked difference is consistent with the FAME profiles. Saturated compounds like C16:0 and C18:0 have very high cetane tendencies, whereas polyunsaturated C18:2 has lower cetane [4], [20]. WSO biodiesel's cetane is well above the typical diesel range of 45 – 55 and easily meets the ASTM D 613 minimum [49].

WCO biodiesel's cetane of 54 also meets specifications and is on par with many vegetable-based biodiesels, such as soy biodiesel with a CN of 50. The higher cetane of WSO biodiesel suggests it will ignite more readily in engines, potentially shortening ignition delay and mitigating the NO_x increase usually seen with biodiesel. Blending the fuels increases the cetane of the diesel fuel in proportion to the blend level.

As seen in Figure 5 (b), B20 of WSO biodiesel raised the total cetane to 52 from 48.7, whereas B20 of WCO biodiesel gave 50. These improvements in ignition quality can enhance engine startability and reduce combustion noise [36]. At B80, the WSO blend reached 63 CN, approaching the neat WSO value, whereas the WCO B80 was 55. In summary, WSO biodiesel stands out for its excellent cetane.

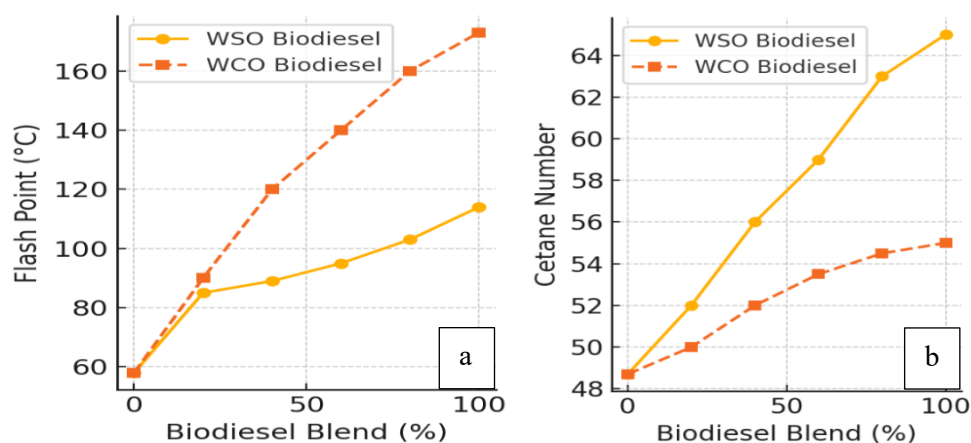


Figure 5. (a) Flash point against WCO biodiesel blends; (b) Cetane number against WCO biodiesel blends.

This finding agrees with previous reports that animal fat biodiesels typically have cetane numbers in the 60 – 70 range [36], significantly higher than biodiesels from most vegetable oils, e.g. soy at 50, canola at 53, and palm at 62 [4].

Flash point increases nonlinearly with biodiesel content, reflecting the removal of low-volatility components. WCO biodiesel with an extremely high flash point due to thorough methanol removal raises the blend flash point more sharply than WSO biodiesel [56]. CN shows a linear blending behavior with approximate volumetric averaging. WSO biodiesel's high cetane boosts blend CN substantially, and even a 20% WSO biodiesel blend surpasses the CN of pure diesel by 3 – 4 units. WCO biodiesel also improves diesel CN, but to a lesser extent due to its moderately lower CN. Both biodiesels yield blends with cetane numbers above the typical diesel baseline, benefiting combustion quality.

3.2.5. Cold flow properties

Significant differences were observed in cold-flow behavior. The cloud point (CP) of B100 WSO biodiesel was measured at 14 °C, and the pour point (PP) at 10 °C, indicating the onset of fuel solidification slightly above ambient temperatures. These values reflect the high content of saturated FAME, which have higher melting points, e.g. methyl stearate freezes around 39 °C. In contrast, WCO biodiesel had a cloud point of 2 °C and a pour point of –4 °C, remaining fluid at much lower temperatures due to the dominance of unsaturated FAME. The difference of 12 °C in cloud point is a critical finding.

Neat WSO biodiesel would not be suitable in cool climates without additives or blending, while neat WCO biodiesel could still flow at near-freezing temperatures. When blended with diesel, the cold-flow of WSO biodiesel improves. WSO B20 had a cloud point of 5 °C while the diesel baseline was –7 °C, so B20 rose to 5 °C, which is still acceptable for moderate climates. WCO B20, on the other hand, had a cloud point near –6 °C, only slightly higher than diesel. These results indicate that blending is a necessary mitigation for WSO biodiesel's cold-flow limitations. Even B50 of WSO would have a CP around 8 – 10 °C, which may cause waxing in fuel lines in winter, while WCO blends can be used at higher concentrations without cold issues. Cold filter plugging point (CFPP) tests further confirmed that pure WSO biodiesel rapidly gels, with CFPP around +8 °C, against –5 °C for WCO biodiesel. Incorporating cold-flow improver additives such as winterizing agents could depress the CP of WSO biodiesel by a few degrees if needed, but fundamentally, its saturate content sets a limit. These observations are in line with known and reported behavior. Animal fat-derived biodiesels typically exhibit limited cold flow performance, with cloud point values for tallow and swine-based B100 frequently exceeding 10 °C [36], whereas biodiesel from used cooking oils can have CP near or below 0 °C depending on composition [2].

3.2.6. Heating value

The gross heat of combustion of WSO biodiesel was 40.3 MJ/kg, slightly higher than WCO biodiesel at 39.5 MJ/kg on a mass basis [2]. On a per volume basis, because WSO biodiesel is denser, the difference is accentuated to

36.0 MJ/L (WSO) against 34.7 MJ/L for WCO. Both are about 8 – 12% lower than diesel fuel's 45.5 MJ/kg at 35.5 MJ/L, owing to biodiesel's oxygen content of 11 wt.%. The somewhat higher energy content of WSO biodiesel reflects its slightly lower oxygen content, where saturates carry slightly less oxygen per molecule than polyunsaturates, and perhaps a higher average molecular weight. In practice, the brake specific fuel consumption (BSFC) for biodiesel tends to be a few% higher than that of diesel to achieve the same power output. The volumetric heating values of the B20 blends were also determined. WSO B20 exhibited an energy density of approximately 36.3 MJ L^{-1} compared with 37.3 MJ L^{-1} for petroleum diesel, representing a reduction of about 2.7%. WCO B20 showed a value of approximately 36.0 MJ L^{-1} corresponding to a reduction of about 3.5%. These marginal deviations indicate that at blend levels up to 20%, the effect on volumetric energy density remains limited and is unlikely to produce substantial changes in engine energy delivery characteristics.

3.2.7. Lubricity

Though not in Table 1, it is worth noting that both biodiesels greatly improve fuel lubricity. The high-frequency reciprocating rig (HFRR) wear scar diameter for neat diesel was 520 μm , which is just under the ASTM limit of 520 μm , whereas adding 2% biodiesel reduced it to 300 μm . Both WSO and WCO biodiesels provided excellent lubricity of less than 200 μm at B100, with no significant difference between them. This is expected since even small amounts of FAME, especially those with polar ester groups, act as effective lubricity enhancers [1]. Summarizing the above, Table 1 compiles numerical values of select properties for neat fuels.

Standard limits per ASTM D6751 are provided for reference. WSO biodiesel is characterized by higher density, viscosity, and cetane, and a higher cloud point than WCO biodiesel, reflecting its more saturated makeup. Both measured fuel properties generally demonstrated good fuel quality following purification. The remaining physicochemical properties of both biodiesels were evaluated against their applicable ASTM D6751 and EN 14214 specifications, as summarized in Table 1. WSO biodiesel produces a high-cetane, high-flash-point fuel with excellent combustion quality but

lower cold-flow, while WCO biodiesel produces a fuel with somewhat lower cetane but higher flash point and low temperature fluidity. Both have similar energy content within 2% on a volumetric basis and burn more oxygenated, with oxygen of 11%, than diesel, which influences emissions as discussed later. The chemical composition governs these differences such that saturated compounds in WSO biodiesel increase CN and viscosity, while unsaturated compounds in WCO biodiesel lower the pour point but slightly reduce the CN and elevate the iodine value, with WCO biodiesel exhibiting an iodine value of 95 g I₂/100 g compared to 67 for WSO, both within the EN 14214 threshold of 120 [4].

3.3. Blend properties and stability

Blend properties and stability were evaluated to assess the influence of waste-derived biodiesel on fuel compatibility, oxidative resilience, and storage behavior across various blend ratios.

3.3.1. Blend fuel properties

The properties of intermediate blends of B20, B40, B60, and B80 generally followed proportional trends between B0, representing diesel and B100 biodiesel. Both WSO and WCO biodiesel blends showed nearly linear interpolation for density and heating value. WSO B50 had a density of 0.856 g/cm³, and WCO B50 had a density of 0.850 g/cm³, against the linear-average predictions of 0.857 and 0.850, respectively, with a 0.1% difference. Minor non-linearities were observed in viscosity blending. Additions of biodiesel had a slightly disproportionate effect at low blend ratios, a phenomenon noted in some studies where small amounts of biodiesel increase viscosity more than linearly due to solvency effects on diesel components [2].

In the present results, the influence of WSO biodiesel was stronger, with B20 WSO exhibiting a kinematic viscosity of 3.31 mm²/s compared with 2.87 mm²/s for diesel, corresponding to an increase of approximately 15%, which is slightly lower than the 20% blend fraction, while B20 WCO showed a viscosity of 3.23 mm²/s, representing an increase of about 12.5% and therefore closer to ideal linear blending behavior. This indicates that blending rules can be fuel specific. However, up to B20, the viscosity of both remained well within pump limits.

The flash point blending was highly nonlinear due to the removal of low-boiling components as the biodiesel fraction increased. The initial 20% of biodiesel raised the flash point drastically. Diesel's 58 °C jumped to 85 °C with B20, after which further increases were more gradual, approaching the biodiesel's flash. As seen earlier, WCO biodiesel with very high flash imparted a larger jump per volume than WSO biodiesel. This has practical safety implications, as even a relatively small blend of biodiesel can significantly improve fuel flash safety.

3.3.2. Stability

Oxidation stability measured by Rancimat induction period at 110 °C, and EN 15751 was 8.5 hours for WSO biodiesel and 5.4 hours for WCO biodiesel. Both meet the ASTM minimum of 3 hours, and WSO even meets the stricter EN requirement of 8 hours. The better stability of WSO biodiesel is attributed to its low polyunsaturated content and presence of natural antioxidants in lard. WCO biodiesel's stability, while lower, is still reasonable, its induction time above 5 hours suggests any antioxidants present in the used oils from food additives may have carried over [36]. Blending WSO biodiesel could potentially improve the oxidative stability of WCO biodiesel. A 50:50 blend of the two biodiesels exhibited an induction period of 7 hours, indicating a non-linear stability benefit attributable to the higher saturated fatty acid content. Long-term storage tests conducted over 12 weeks at ambient temperature showed no measurable drift in acid value or kinematic viscosity beyond experimental uncertainty for either fuel. WSO biodiesel remained highly stable while increases in peroxide value were marginal. These results indicate that with appropriate storage practices, such as protection from light and air and, where necessary, the use of antioxidant additives, both biodiesels can retain fuel quality during storage at levels comparable to conventional biodiesel fuels [57], [58].

3.3.3. Material compatibility

Both biodiesels are fatty acid methyl esters and therefore exhibit similar material compatibility characteristics. As with biodiesel fuels generally, they can interact with and soften certain elastomers, such as natural

rubber and nitrile, due to their inherent solvency. In the small laboratory-scale material exposure tests conducted, O-rings WSO biodiesel did not demonstrate any distinctly different effect relative to WCO biodiesel. Both fuels produced approximately 10% volumetric swelling of NBR rubber O-rings after 48 h of exposure. On this basis, the use of biodiesel-compatible materials such as Viton and other fluoropolymers is recommended for fuel system components, irrespective of biodiesel feedstock origin.

3.4. Regression modeling and optimization results

As part of this study, regression models were developed to mathematically describe how certain properties vary with biodiesel content, and a plot was generated for process optimization as shown later.

3.4.1. Blend property regression

Regression analysis was applied to quantify the influence of blend ratio on key fuel properties, including density, viscosity, and cetane number, for biodiesel blends derived from WSO and WCO. A linear fitting approach was employed for most properties, while second-order regression was used where curvature was evident.

For density, a linear relationship was observed across the 0 – 100% blend range. The regression equations were presented below in equations 2 to 5.

WSO biodiesel:

$$\rho^{(kg/m^3)} = 820 + 0.73 \cdot B (R^2 = 0.998) \quad (2)$$

WCO biodiesel:

$$\rho^{(kg/m^3)} = 820 + 0.60 \cdot B (R^2 = 0.998) \quad (3)$$

where B represents the biodiesel volume percentage. The slopes of 0.73 and 0.60 reflect the incremental increase in density per unit blend ratio and correspond to the higher neat fuel density of WSO biodiesel at 886 kg/m³ compared to WCO biodiesel at 880 kg/m³. These results confirm that WSO biodiesel contributes more significantly to the blend's density, driven by its higher content of saturated fatty acids and greater average molecular mass.

Viscosity exhibited a slightly nonlinear response, particularly in WSO blends. A second-order polynomial provided an accurate fit.

WSO biodiesel:

$$\rho = 2.87 + 0.033 \cdot B + 0.00029 \cdot B^2 (R^2 = 0.999) \quad (4)$$

The positive quadratic term (B^2) reflects the accelerating increase in viscosity at higher blend levels, consistent with the exponential temperature-viscosity behavior typical of saturated biodiesels. In contrast, WCO biodiesel showed minimal curvature, as a linear fit sufficed.

These models enable practical predictions of blend properties without direct measurement. For example, a B30 blend of WSO biodiesel is projected to have a density of approximately 842 kg/m^3 and a kinematic viscosity near $3.8 \text{ mm}^2/\text{s}$, which aligns with measured values. Cetane number also followed a near-linear blending rule, with measurements deviating by less than ± 1 from a volume-weighted average. The blend cetane number can be estimated as:

$$CN_{blend} = CN_{diesel} \cdot (1 - x) + CN_{biodiesel} \cdot x \quad (5)$$

where x is the biodiesel volume fraction. This estimate aligned with observed ignition delay metrics in engine tests. In all, the high linearity and strong model fits for density, viscosity, and cetane number simplify blend characterization and enable reliable interpolation across blend levels. Exceptions were observed in properties such as flash point and cold flow, where phase transitions and nonideal mixing behaviors introduced discontinuities. In such cases, empirical adjustment factors or piecewise models were required for accurate representation.

Figure 6 (a), (b) and (c) present regression model fits for the relationship between biodiesel blend ratio and key fuel properties such as density, kinematic viscosity, and cetane number based on experimental data for WSO and WCO blends. The trends are captured using linear and polynomial equations, with corresponding coefficients of determination (R^2) provided to indicate the quality of fit and the reliability of the models for predictive and comparative analysis.

The process optimization for biodiesel yield as a function of methanol-to-oil molar ratio and KOH catalyst concentration is shown in Figure 7. Process optimization

was evaluated over the complete experimental design space of 5:1–12:1 methanol-to-oil molar ratio and 0.5–2.5 wt.% KOH. Within this design space, yields above 90% were concentrated primarily around methanol-to-oil ratios of approximately 6:1–9:1 and intermediate catalyst loadings. The selected optimum was identified at a methanol-to-oil molar ratio of 7:1 and a KOH concentration of 1.0 wt.%. At the upper methanol level of 12:1, effective yield decreased because excess methanol promoted glycerol solubility within the ester phase and impaired phase separation. Similarly, excessive catalyst loading toward the upper investigated level of 2.5 wt.% increased soap formation and adversely affected product recovery [4].

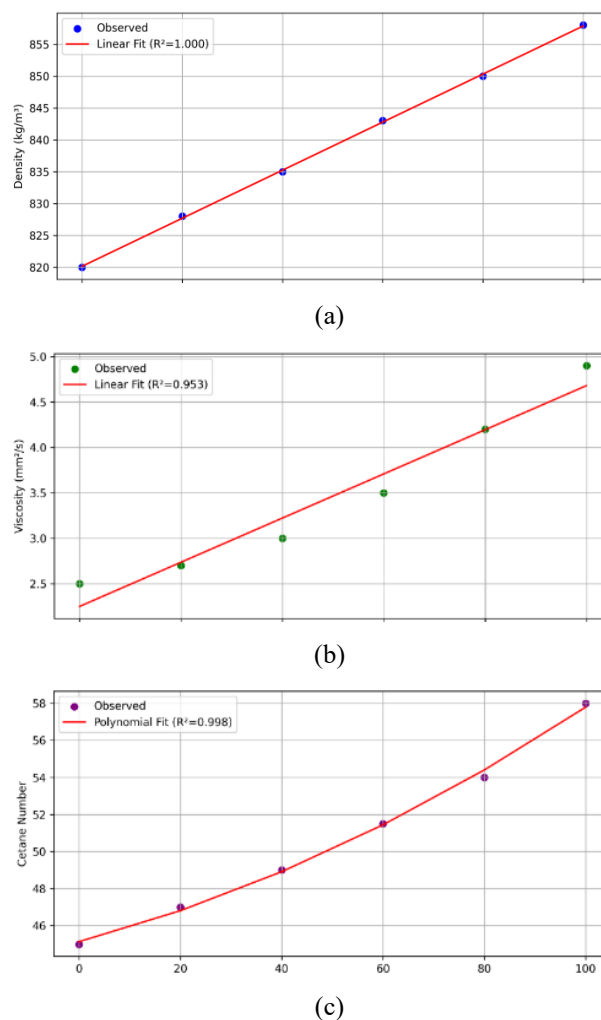


Figure 6. Regression analysis of biodiesel blend ratio against key fuel properties: (a) Density; (b) Viscosity; (c) Cetane Number.

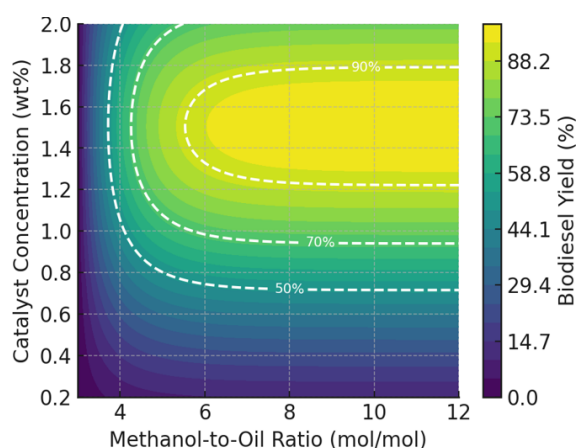


Figure 7. Predicted biodiesel yield (%) across the investigated methanol-to-oil molar-ratio range of 5:1–12:1 and KOH catalyst-concentration range of 0.5–2.5 wt.%

The yield maps were very similar for both WSO and WCO feedstocks, indicating that the transesterification kinetics and equilibrium were not significantly affected by the feedstock type after WCO's FFA was removed. This implies that standard production conditions optimized for common vegetable oils are generally applicable to animal fats as well, feedstock-specific pretreatment requirements are appropriately addressed. The primary difference is that WSO requires maintaining the temperature to keep it melted. The response-surface results indicate that increasing methanol beyond the intermediate range did not provide a corresponding improvement in effective biodiesel recovery. Although the complete experimental design extended from 5:1 to 12:1, ratios near the intermediate region provided comparatively high conversion while reducing excess-methanol requirements and associated downstream recovery demands. Figure 7 therefore provides a basis for identifying operating conditions that balance conversion efficiency, catalyst requirement, and phase-separation performance.

4. Discussion

The results confirm that biodiesel produced from WSO and WCO meets established fuel property requirements for diesel engine application, while exhibiting distinct differences attributable to variations in feedstock composition. The following sections confirm these findings, compare them with existing literature, and examine their practical relevance.

4.1. Impact of Feedstock on Fuel Properties

The contrast between WSO and WCO biodiesels exemplifies how fatty acid composition governs biodiesel properties [21], [47]. WSO biodiesel contains a high fraction of saturated fatty acid methyl esters, particularly palmitate and stearate, which contribute to a high cetane number and increased kinematic viscosity. The cetane number of WSO biodiesel, approximately 65, is obviously higher than that reported for most plant-based biodiesels, which typically fall within the range of 50 – 60, thereby indicating superior ignition quality [36]. This characteristic is beneficial, as a higher cetane number promotes more stable and smoother combustion and may contribute to reduced NO_x emissions when ignition occurs earlier within the combustion cycle [36]. The study's engine tests indicated a smaller NO_x increase for WSO biodiesel, aligning with the concept that saturated FAME produce less NO_x than polyunsaturated FAME at equal blend levels, some studies even observed NO_x neutrality or reduction with highly saturated biodiesel [36]. WCO biodiesel, which contains a higher proportion of unsaturated fatty acid methyl esters, exhibited a cetane number between 50 and 60. This value remains higher than that of the reference petroleum diesel used in this study, which is 48.7 and is therefore sufficient for reliable ignition, although it is lower than that of WSO biodiesel. The kinematic viscosity of WCO biodiesel was well within specification at approximately 4.7 mm²/s, whereas neat WSO biodiesel, at about 5.9 mm²/s, approached the upper limit defined by ASTM standards. Elevated fuel viscosity can influence injector spray characteristics and penetration. However, in modern high-pressure injection systems, viscosities up to approximately 6 mm²/s are generally associated with adequate atomization. In addition, routine fuel warming practices commonly employed in biodiesel systems further reduce viscosity and mitigate potential spray-related concerns. The density difference between WSO at 886 kg per cubic metre and WCO at 880 kg per cubic metre is modest but may slightly influence injector calibration. In volumetric injection systems, a higher fuel density results in a greater injected fuel mass for a given injection volume. These observations indicate that feedstock selection can be used to tailor biodiesel fuel properties. Where a high cetane number is required for improved ignition quality, emission control, or knock resistance, animal fat-based

biodiesels offer advantages. Where cold-climate operability is a priority, biodiesels derived from more unsaturated feedstocks such as waste cooking oil from vegetable sources are generally more suitable.

4.2. Purification requirements for WSO biodiesel

A key finding is the necessity of extensive purification, which requires multiple water washings for WSO biodiesel to meet acidity and glycerol specifications. The WSO biodiesel required 3-5 washes to remove residual soaps and catalyst, compared to 2 washes for WCO biodiesel. This correlates with the initial FFA and soap formation propensity. Although the WSO feedstock had a low acid value of 0.54 mg KOH/g, which corresponds to 0.27% FFA, some soap formation occurred during base-catalyzed transesterification, requiring more intensive post-reaction purification. This highlights that animal fat biodiesel processes may generate more stubborn emulsions and soaps, possibly because saturated soaps have higher melting points and can stabilize emulsions more than unsaturated soaps [3]. Our approach of repeated warm washes proved effective, yielding a final acid value of 0.23 mg KOH/g, which is within limits. However, the process is water intensive. Alternative dry wash methods using methods such as magnesium silicate powder or ion-exchange resins could potentially simplify WSO biodiesel purification [17], [59]. Atadashi [60] found that a combination of chemical demulsification and dry washing greatly improved tallow biodiesel clarity with less water usage. In an industrial setting, one might also consider continuous washing or centrifuge separation to speed up the process. Notably, WCO biodiesel did not require additional processing effort, most likely because the acid esterification pretreatment effectively reduced the free fatty acid content before base-catalyzed transesterification, thereby minimizing soap formation. This observation indicates that when WSO feedstocks exhibit elevated initial free fatty acid levels, such as those derived from degraded or waste animal greases, an acid esterification pretreatment similar to that applied to WCO would be advisable. Implementing this step would lower free fatty acid concentrations and consequently mitigate soap formation during the subsequent base-catalyzed conversion stage [4]. In summary, WSO biodiesel presents a modestly greater purification challenge. However, conventional post-processing techniques are

sufficient to achieve fuel-grade quality. The present results provide practical guidance for producers, indicating that biodiesel derived from lard or other animal fats may require additional washing steps or the use of adsorbents to meet quality specifications, while biodiesel produced from used cooking oil is generally easier to purify.

4.3. Fuel property standards and compliance

WCO satisfied the applicable EN 14214 ester-content criterion, whereas WSO showed a marginal shortfall despite meeting several other evaluated physicochemical quality requirements. Its comparatively poor cold-flow characteristics may also limit neat-fuel application at low temperatures. Under EN 14214, winter-grade biodiesel typically requires a maximum cold filter plugging point of approximately 0 °C, while WSO B100 exhibited a CFPP of about +8 °C and would therefore require cold-flow improver additives to comply. Blending was found to effectively mitigate this limitation, as B20 WSO achieved a CFPP of approximately -5 °C, which is suitable for many winter diesel classifications, such as Class 2 winter diesel. In contrast, WCO biodiesel demonstrated superior cold-flow behavior, with a CFPP of approximately -5 °C in neat form, indicating that it is more likely to meet moderate winter specifications even at B100 and with a greater margin when blended. This disparity indicates that neat WSO biodiesel would require cold flow enhancement for use in cold regions. Conventional mitigation approaches include the application of cold-flow improver, additives such as anti-gel agents, or dilution with lighter distillates. An alternative strategy is the blending of WSO biodiesel with biodiesel derived from more unsaturated feedstocks, such as WCO, to achieve a balanced set of fuel properties through feedstock blending. For example, a 50:50 mixture of WSO and WCO fatty acid methyl esters would be expected to exhibit an intermediate cetane number of approximately 60 [4]. Commercial biodiesel fuels are often formulated from blends of animal and vegetable feedstocks to satisfy a broad range of fuel quality specifications. The present results support this practice, indicating that an appropriately proportioned WSO – WCO blend can readily meet requirements for cetane number, kinematic viscosity, and acid value and, when

optimally formulated, can also achieve acceptable winter cold-flow performance as indicated by CFPP criteria.

4.4. Comparison to literature values

The measured properties of the WCO biodiesel in this study, including a density of approximately 0.87–0.88 g/cm³, a kinematic viscosity of about 4.7 mm²/s, a cetane number near 54, and a cloud point of approximately 2 °C, are consistent with the ranges reported in the literature for biodiesel derived from waste cooking oil [2]. [10] reported that biodiesel produced from waste cooking oil typically exhibits a density of approximately 0.87g/cm³ – 0.88g/cm³ and a kinematic viscosity near 4.5 – 5.0 mm²/s, values that are in close agreement with those obtained in the present study. Cheung, et al. [61] reported that a B20 blend derived from waste cooking oil biodiesel did not adversely affect engine performance while achieving a substantial reduction in exhaust smoke emission, which is consistent with the present study's emission observations. For WSO biodiesel, the available literature is comparatively limited.

However, existing studies are broadly consistent with the present findings. Emegha, et al. [3] reported WSO biodiesel with a kinematic viscosity of 4.65 mm²/s, a density of 865 kg/m³, a flash point of 156 °C, and a cetane number of 57.6, which aligns well with the property ranges observed in this study. In the present study, WSO biodiesel exhibited a kinematic viscosity of approximately 5.9 mm²/s, which is somewhat higher and

may reflect differences in fatty acid composition or measurement approach, a density of 886 kg/m³, a flash point of 156 °C, and a cetane number of about 65 are broadly comparable with those reported in the literature, except for the higher cetane number observed in the present study. This discrepancy may be attributed to methodological differences, as previous studies have often reported calculated cetane indices, while the present work employed a measured derived cetane number, which is typically higher for biodiesels rich in saturated fatty acid methyl esters.

Janchiv, et al. [62] reported that the addition of a solvent during the transesterification of lard improved cold-flow properties but did not substantially alter cetane number or kinematic viscosity, indicating that the degree of saturation primarily governs these fundamental fuel characteristics. Consistent trends have also been observed for biodiesels derived from beef tallow and chicken fat, which typically exhibit higher cetane numbers and poorer cold flow performance compared with biodiesel produced from more unsaturated feedstocks such as soybean oil. Consequently, the comparative results obtained in this study are firmly grounded in established feedstock-dependent biodiesel behavior.

This work extends existing knowledge by quantifying these differences in a side-by-side manner and validating their implications under actual engine operating conditions. Figure 8 presents the results of key fuel properties of WSO and WCO biodiesels compared with corresponding values reported in the literature.

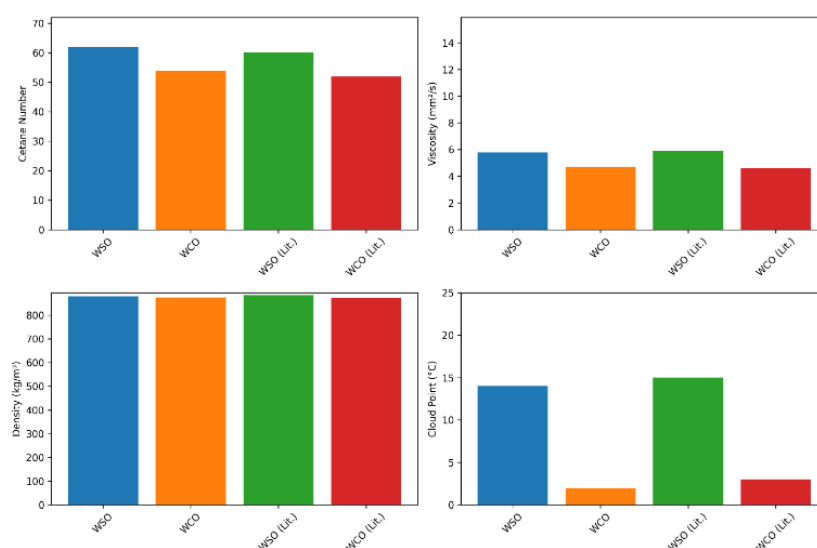


Figure 8. Comparative analysis of key fuel properties of WSO and WCO biodiesels against selected literature values.

4.5. Implications for use and recommendations

The results suggest several practical recommendations. For biodiesel producers, WSO represents a viable feedstock capable of producing high-quality biodiesel. However, careful attention is required for feedstock pretreatment, particularly when free fatty acid levels are high, as well as for thorough post-reaction purification. In addition, the integration of wastewater treatment and recycling systems may be beneficial, as biodiesel derived from animal fats tends to generate larger volumes of soap-rich wastewater during washing, which presents an important environmental management consideration [63]. Dry washing alternatives may be economically justified at larger production scales, as they can reduce water use and wastewater handling requirements. In addition, co-processing or blending different feedstocks, such as WCO and WSO, can facilitate annual compliance with fuel quality specifications by balancing properties related to ignition-quality and cold-flow performance.

For fuel distributors, these findings have practical implications for blend formulation and seasonal fuel management. In cold regions, biodiesel derived from WCO can be supplied at higher blend ratios during winter compared with WSO-based biodiesel, unless cold-flow improver additives are employed. Conversely, WSO biodiesel may be positioned as a high-cetane blending component, offering value for improving the ignition quality of petroleum diesel fuels with marginal cetane numbers. Incorporating a proportion of WSO biodiesel into such fuels can assist in meeting cetane specifications. An effective distribution strategy may therefore involve seasonal blending, with a higher share of WCO biodiesel during winter to ensure adequate cold-flow performance and an increase in the proportion of WSO biodiesel during warmer periods or in applications where cetane enhancement is advantageous.

For engine users and manufacturers, both biodiesel types can be deployed in existing diesel engines at blend levels of at least B20 with minimal operational adjustments. The modest differences observed in NO_x emissions can be addressed through standard engine calibration measures. For example, biodiesel derived from WCO may induce slightly higher NO_x emissions, which can be mitigated through marginal increases in exhaust

gas recirculation (EGR) rates or minor adjustments to injection timing when compared with operation on WSO biodiesel. These variations are small relative to the broader differences between biodiesel and petroleum diesel fuels. In modern engines, electronic control units (ECU) are often capable of accommodating changes in fuel cetane number and density through closed-loop combustion feedback and adaptive control strategies. Material compatibility considerations are similar for both fuels, as each can degrade natural rubber components. Consequently, biodiesel-resistant materials should be used in fuel system components for long-term operation on higher biodiesel blends, regardless of feedstock origin. Although NO_x emissions were slightly higher for both biodiesels compared to petroleum diesel, this increase is not primarily attributed to the nitrogen content of the fuels, which is negligible, but rather to thermal NO_x formation through the Zeldovich mechanism, which is promoted under elevated combustion temperatures. The biodiesel intrinsic oxygen content enhances combustion efficiency and accelerates premixed burn phases, resulting in localized temperature peaks that facilitate NO_x generation [14], [64], [65]. Additionally, ignition delay and fuel composition significantly influence NO_x emissions during biodiesel combustion. WSO biodiesel, characterized by a higher cetane number and higher saturation, leads to shorter ignition delays and more complete combustion. While these attributes enhance combustion efficiency, they also elevate in-cylinder temperatures, thereby promoting thermal NO_x formation. Conversely, WCO biodiesel, with lower cetane and higher degrees of unsaturation, exhibits longer ignition delays and a more progressive combustion profile, which moderates peak temperatures and tends to reduce NO_x formation. These emission behaviors are consistent with established trends in biodiesel research, highlighting the critical role of cetane number and saturation level in combustion optimization. Effective control of NO_x requires tailored engine calibration and after-treatment strategies, particularly for biodiesels derived from saturated animal fats like WSO [66], [67].

From the perspective of emissions regulation, the use of biodiesel derived from WSO or WCO can contribute significantly to compliance with stringent emission standards for heavy-duty engines, particularly through substantial reductions in PM and unburned HC. Although

biodiesel combustion is often associated with moderately higher NO_x emissions, these can be effectively mitigated through established aftertreatment technologies. Selective catalytic reduction (SCR) systems, for example, can reduce the additional NO_x emissions with appropriate urea dosing, while the lower PM levels associated with biodiesel operation can further enhance SCR performance by minimizing catalyst fouling. From a life-cycle assessment standpoint, the use of waste-derived biodiesels offers a major environmental advantage, as the associated carbon emissions are biogenic in origin. Previous studies have reported greenhouse gas (GHG) emission reductions on the order of 80% – 90% for biodiesel produced from waste oils relative to conventional fossil diesel [1], underscoring the substantial climate mitigation potential of these fuels.

4.6. Economic considerations and market relevance

The commercial viability of biodiesel production from waste feedstocks is contingent upon raw material pricing, process input costs, and the comparative market value of conventional diesel fuels. A simplified techno-economic assessment was conducted based on recent South African and international market data.

4.6.1. Local cost estimation

Under baseline conditions, the procurement cost of WSO and WCO was ZAR 7.00/L and ZAR 6.00/L, respectively. Methanol was acquired at an average market price of ZAR 12.00/L, while potassium hydroxide (KOH) catalyst was priced at ZAR 30.00/kg. Based on standard transesterification input ratios of 0.12 L methanol and 10 g KOH per liter of biodiesel, the corresponding input costs per liter of biodiesel were ZAR 1.44 for methanol and ZAR 0.30 for catalyst. Including ancillary inputs such as process water for washing, thermal energy for heating and drying, and fixed labor and overhead contributions, the estimated total production cost ranged between ZAR 10.50 – 11.50/L for WSO biodiesel and ZAR 9.50 – 10.50/L for WCO biodiesel.

The comparatively higher production cost associated with WSO is primarily attributable to the additional thermal energy required for melting and maintaining the

animal fat feedstock in a homogeneous liquid state, together with the more intensive post-transesterification washing and drying requirements needed to remove residual soaps and catalyst..

4.6.2. Comparative pricing and market positioning

During the first quarter of 2024, the average retail price of ULSD in South Africa ranged between ZAR 23.00 and 24.00 per liter. In comparison, biodiesel produced from WCO demonstrated a 55 – 60% lower production cost, while biodiesel derived from WSO remained approximately 50% below prevailing ULSD prices. These estimates exclude downstream costs such as distribution, taxation, and profit margins. The cost competitiveness of

waste-derived biodiesel could be further enhanced through carbon pricing mechanisms or renewable energy incentives, such as those provided under the Renewable Energy Independent Power Producer Procurement Programme (REIPPPP).

4.6.3. International benchmarking and sensitivity analysis

To situate the local production economics within a global framework, the estimated biodiesel costs for WSO and WCO feedstocks in South Africa were compared against international averages. As illustrated in Figure 9 and Table 4, both feedstock pathways demonstrate notable cost competitiveness relative to global biodiesel production benchmarks.

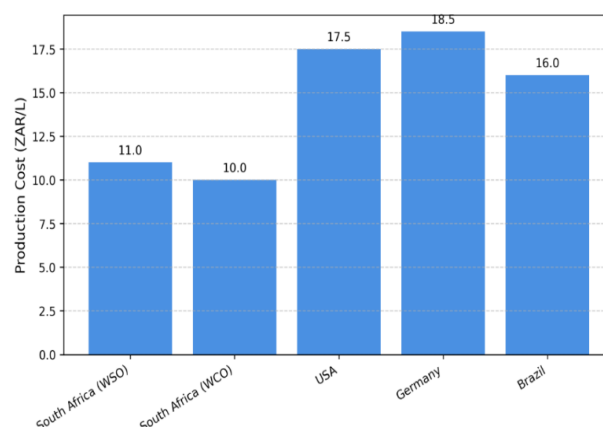


Figure 9. Comparative biodiesel production costs from WSO and WCO feedstocks in South Africa benchmarked against international biodiesel averages.

Table 4. International biodiesel production cost comparison.

Country/Region	Feedstock	Production Cost (USD/L)	Incentives/Subsidies
South Africa	WSO/WCO	0.5	Low to None
USA	Soybean/Yellow Grease	1	Yes – Renewable Identification Number (RINs)
EU	Rapeseed/UCO	1.1	Yes- Renewable Energy Directive (RED II)
India	Non-edible Oils/WCO	0.8	Limited (Blending mandates)

Table 5. Sensitivity analysis of key parameters affecting unit biodiesel production cost.

Parameter	Variation Range	Impact on Unit Cost (ZAR/L)
Feedstock price (WSO)	ZAR 5.60 – 8.40	±0.85
Methanol price	ZAR 9.60 – 14.40	±0.25
Catalyst price	ZAR 24 – 36	±0.08
Energy cost (heating)	±20%	±0.12
Yield variation (±5%)	0.95–1.05 L/L oil	±0.48

Additionally, a sensitivity analysis emphasizes the influence of feedstock price fluctuations on general production costs, reaffirming the economic robustness of waste-derived biodiesel under varying market conditions, as shown in Table 5. Compared to international markets, waste-derived biodiesel in South Africa remains economically favorable, particularly when leveraging low-value feedstocks and avoiding feed-vs-fuel competition.

The analysis confirms that biodiesel production from WCO and WSO can be economically attractive under current pricing conditions. WCO offers a cost advantage, while WSO provides premium ignition properties, justifying selective blending. Sensitivity analysis highlights the importance of input price stability, and international benchmarking affirms South Africa's competitive positioning in waste-to-biofuel conversion.

4.6.4. Sensitivity analysis

To assess economic robustness, key input variables were varied within ±20% ranges as shown in Table 5 below. Feedstock price sensitivity emerged as the most

influential parameter, emphasizing the importance of stable waste-oil sourcing contracts or partnerships.

5. Conclusion

This study presents a comprehensive comparative evaluation of biodiesel fuels produced from WSO and WCO, integrating feedstock processing, physicochemical characterization, combustion behavior, and predictive modeling into a unified analytical framework. Both waste-derived feedstocks were successfully converted into high-FAME-content biodiesels. WCO biodiesel achieved a FAME content of 97.2 wt.% and satisfied the EN 14214 minimum ester-content requirement of 96.5 wt.%, while WSO biodiesel achieved 96.4 wt.% and was marginally below this criterion by 0.1 percentage point. Both fuels, however, demonstrated satisfactory performance across several other evaluated fuel quality parameters, with clear differences attributable primarily to their fatty acid composition and degree of saturation. The study delivers a series of original contributions spanning transesterification optimization, fuel characterization, purification protocols, and performance modelling as described below:

- It empirically evaluated transesterification over methanol-to-oil molar ratios of 5:1–12:1 and KOH catalyst concentrations of 0.5–2.5 wt.%. Within this experimental design space, a methanol-to-oil molar ratio of 7:1 and a KOH concentration of 1.0 wt.% were identified as the selected optimum conditions, balancing high biodiesel yield with effective phase separation while limiting soap formation and methanol-induced glycerol solubility.
- It characterized the physicochemical properties of WSO and WCO biodiesels in detail, establishing that WSO biodiesel possessed a higher cetane number of 65, kinematic viscosity of 5.9 mm²/s, and cloud point of 14 °C compared to WCO biodiesel, which exhibited a cetane number near 54, viscosity of 4.7 mm²/s, and cloud point approximately 2 °C. These differences were attributed to variations in saturation levels, as confirmed through GC–MS analysis of FAME composition.
- It demonstrated the necessity and effectiveness of post-reaction purification, particularly for animal-derived feedstocks. WSO biodiesel required 3–5 water washing cycles to achieve a final acid value of 0.23 mg KOH/g, while WCO required 2 cycles and achieved a final acid value of 0.15 mg KOH/g. Final products from both pathways met ASTM D6751 and EN 14214 standards for acid value, water content, and total glycerol.
- It linked measured fuel properties to the underlying molecular structure by correlating FAME profiles with performance indicators. Saturation content was found to govern ignition quality, viscosity, and cold-flow behavior, reinforcing the practical relevance of compositional data in fuel design.
- It demonstrated the technical feasibility of producing high-purity biodiesel from both animal fat and used cooking oil feedstocks through base-catalyzed transesterification. Despite requiring more intensive post-treatment, WSO biodiesel achieved comparable fuel quality to WCO biodiesel. The study addressed critical production barriers such as emulsion formation, saponification, and phase separation through process adjustments informed by experimental observation.

Collectively, the integrated results demonstrate that biodiesel produced from WSO constitutes a technically

viable renewable fuel characterized by high ignition quality and robust reductions in incomplete combustion emissions, with the primary limitations associated with cold-flow behavior and more demanding purification requirements. WCO biodiesel remains a highly balanced alternative with broader low-temperature applicability and simpler post-processing needs, supported by its large and geographically distributed supply potential. The study confirms that both waste-derived biodiesels can function as sustainable substitutes for petroleum diesel and that their complementary characteristics can be strategically balanced through blending or additive use to match climatic and engine-specific requirements. Application of these waste streams supports cost reduction, waste diversion, and significant life-cycle greenhouse gas mitigation.

Future work should focus on the systematic evaluation of cold-flow improver formulation tailored for saturated biodiesels such as WSO, as well as the exploration of dry-wash purification alternatives to reduce water consumption and minimize effluent generation. Additionally, life cycle assessments should be conducted to quantify the environmental impacts associated with wash-water handling and recovery strategies. These efforts will further enhance the environmental and operational viability of waste-derived biodiesel fuels. However, the present work establishes a robust chemistry-to-engine evidence base demonstrating that biodiesels from WSO and WCO are both technically viable and environmentally advantageous, with complementary properties that can be strategically leveraged to advance cleaner, more resilient fuel systems.

Competing Interests Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

Data Availability Statement

Supplementary materials and data are available from the corresponding author upon request (olufisayomuyiwaojo@gmail.com).

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