

Effects of Waste Frying Oil Hybridization Ratios on Biodiesel Physicochemical Properties

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Abstract: Waste frying oils (WFOs) represent a promising low-cost feedstock for biodiesel production. However, biodiesel derived from single-source WFOs often exhibits variable physicochemical properties due to differences in fatty acid composition, which can affect fuel quality and compliance with international standards. Therefore, strategies to optimize biodiesel properties through feedstock management remain an important research challenge. This study investigates the effect of feedstock hybridization by hybridizing waste frying oils derived from palm, sunflower, and corn to improve biodiesel fuel characteristics. Several hybrid feedstock ratios (9S:1C, 9S:1P, 8S:1P:1C, 6S:2P:2C, 4S:3P:3C, 5S:5P, 5C:5P, and 5S:5C) were prepared and converted to biodiesel via transesterification, followed by physicochemical characterization including density, kinematic viscosity, acid value, cloud point, pour point and other properties according to ASTM standards. The results show that different ratio of feedstock hybridization influences biodiesel quality, with hybrid proportions of sunflower and corn WFO exhibiting different values. Among the evaluated formulations, the 5S:5C (sunflower–corn) hybrid showed the lowest cloud point (-9.0 ± 1.4 °C) and pour point (-11.0 ± 0.8 °C), together with a density of 875.5 ± 0.7 kg m⁻³, kinematic viscosity of 4.05 ± 0.5 mm² s⁻¹ and acid value of 0.30 ± 0.10 mg KOH/g. The hybrid also exhibited a free fatty acid content of $0.15 \pm 0.03\%$, flash point of 151.1 ± 0.2 °C, saponification value of 200.8 ± 1.2 mg KOH/g, and calorific value of 41.2 ± 1.0 MJ/kg. The results indicate that feedstock hybridization can modify selected biodiesel properties, particularly cold-flow characteristics. These findings show that ratio-controlled hybridization of waste frying oil feedstocks is an effective strategy for improving biodiesel quality while promoting waste valorization and supporting sustainable bioenergy production within a circular economy framework.

Keywords: Waste frying oils; biodiesel; renewable energy; FAME; hybrid ratio; cold-flow properties; physicochemical characterization.

1. Introduction

The demand for effective sustainable resource management has grown due to the convergence of pressure from the growing risk of energy insecurity, the degradation of the environment and the ever-increasing volume of waste being produced globally (Shakir et al., 2024). Thus, it appears that converting post-consumer waste frying oils (WFOs) to biodiesel is an integrated solution aligned to the principles of circular bio-economy and strategies for low-carbon energy transitions. The portion of post-consumer cooking oils are disposed of in a manner harmful to the environment. For example, improper disposal can lead to sewer blockages, contaminate aquifers and degrade soils. Additionally, these oils are underutilized as lipid rich renewable resources. The conversion of WFOs through physicochemical pathways (most commonly base- or acid-catalyzed transesterification) enable the conversion of pollutant prone residues to fatty acid methyl esters (FAME) that are suitable for compression ignition engines



(Shalfah et al., 2025). In addition to reducing environmental harm from the improper disposal of waste materials, the conversion of WFOs to biodiesel will also assist in reducing dependence on fossil fuels. Although fossil fuels continue to dominate transportation and industrial markets due to their high energy density and existing infrastructure, the progressive depletion of petroleum resources and the associated greenhouse gas emissions associated with the extraction and consumption of fossil fuels pose serious sustainability risks (Johnsson et al., 2019),(Shakir et al., 2024a).

Due to the increasingly urgent need to develop renewable energy alternatives to fossil fuels due to climate change mitigation commitments and the ongoing depletion of petroleum resources, the development of renewable alternatives such as biodiesel has been accelerated (Binhweel et al., 2026). The various types of biodiesel feedstocks are generally classified as first, second, third and fourth generations. Initially, first-generation feedstocks were primarily derived from edible crops, including wheat, rice, sugarcane, barley, potatoes and vegetable oils. While first-generation feedstocks were rapidly adopted as a source of biodiesel, they have generated a large amount of public and academic debate regarding their potential impact on food supply chains and agricultural land use due to their relatively high costs and the requirement for large inputs of arable land, irrigation water, fertilizers and agrochemicals (Senusi et al., 2024). These challenges highlight the need to shift towards second- and waste-derived feedstocks that would separate fuel production from food production systems.

One type of second-generation feedstock that could potentially serve as a source of biodiesel is waste frying oils (WFOs) generated from both residential and commercial cooking processes that are typically derived from palm, sunflower and corn oils. Unlike petroleum-based diesel derived from non-renewable fossil resources, WFO-based biodiesel is typically renewable, biodegradable, and associated with lower net greenhouse gas emissions (Kamil et al., 2020). In addition to providing environmental benefits related to the diversion of improperly discarded cooking oils from wastewater treatment plants and landfills, the production of biodiesel from WFOs provides a dual environmental benefit which the reduction of waste disposal-related environmental harm and the replacement of fossil carbon emissions (Senusi et al., 2025),(Binhweel et al., 2024).

The physical and chemical properties of biodiesel are largely determined by the fatty acid composition of the feedstock. Waste frying oils (WFOs) derived from palm oil typically contain higher proportions of saturated fatty acids usually palmitic acid than sunflower or corn oils. Higher saturation generally increases cetane number and oxidative stability, but it can also raise viscosity and worsen cold-flow properties, which may limit engine performance. Hybrid feedstocks with complementary fatty acid profiles provides a practical strategy to balance these trade-offs and meet biodiesel specifications such as density, kinematic viscosity, acid value, cloud point, pour point, and peroxide value in ASTM D6751 or EN 14214.

WFOs frequently exhibit elevated free fatty acid (FFA) concentrations and moisture due to thermal and hydrolytic degradation during frying. High FFA levels promote saponification when alkali catalysts are used for transesterification, reducing ester yields. Therefore, optimization of reaction parameters which including alcohol-to-oil molar ratio, catalyst concentration and reaction temperature which is essential to maximize conversion to fatty acid methyl esters (FAMES) while limiting side reactions. Feedstock hybridization can also affect transesterification kinetics by lowering effective FFA content and improving mass transfer, thereby enhancing overall conversion efficiency.

Although biodiesel production from individual waste frying oils (WFOs) and selected binary hybrids has been widely investigated, systematic comparative studies evaluating multiple hybridizing ratios of palm, sunflower, and corn WFOs remain limited. In particular, there is a lack of comprehensive experimental evidence examining how variations in feedstock composition influence the physicochemical properties and overall fuel quality of the resulting biodiesel under consistent processing conditions.

Accordingly, the present study extends existing research by systematically producing biodiesel from binary and ternary hybrid of palm, sunflower and corn WFOs and evaluating the influence of hybridization ratio on the physicochemical properties including density, kinematic viscosity, acid value, cloud point, pour point, peroxide value, iodine value, and cetane number, in accordance with ASTM and EN fuel standards. Unlike our previous work, which focused primarily on optimizing biodiesel production conditions from selected hybrid WFO feedstocks, the present study emphasizes the comparative assessment of different feedstock hybridization ratio and their relationship with biodiesel quality. The findings provide practical insights into feedstock selection and demonstrate that appropriate hybridization of diverse waste frying oils can improve biodiesel quality while promoting the valorization of underutilized waste resources. Consequently, this work contributes additional experimental evidence supporting the development of sustainable biodiesel production strategies within a circular bioeconomy framework.

2. Materials and Methods

2.1. Sample Collection

In this study, waste frying oil (WFO) samples were obtained from a banana fritter stall on Penang Island, Peninsular Malaysia. Palm, sunflower, and corn WFOs were collected separately from the same vendor after banana frying and transferred into sealed containers to prevent contamination (Figure 1). To ensure a completely uniform baseline matrix for the subsequent hybridization and characterization, the waste frying oils (WFOs) were prepared in a single controlled bulk batch (5 kg) for each feedstock type (palm, sunflower and corn). From each fresh cooking oil batch, approximately 4.7 kg of WFO was collected after frying. The frying process for each feedstock bulk batch was completed within a single day with each frying cycle conducted for 5 min at a temperature of 170–180 °C (Skinner et al., 2021). The samples were taken from every batch for subsequent analysis and biodiesel production. The collected WFO samples were initially filtered through a 500 µm mesh to remove food particles and other impurities. The filtered oils were then transferred into 500 mL glass bottles and stored at room temperature until further analysis. The physicochemical and fatty acid analyses were performed one day after sample collection using pooled WFO samples to minimise changes in their properties during storage. Prior to analysis, residual moisture was removed by oven-drying the samples at 110°C for 40 minute (min)(Yeneneh & Sufe, 2025).



Figure 1. Waste frying oil of palm, sunflower and corn after filtration process. (a) WFO of palm, (b) WFO of sunflower and (c) WFO of corn.

2.2. Transesterification

Various biodiesel hybrids such as 90% sunflower:10% corn (9S:1C), 90% sunflower and 10% palm (9S:1P), 80% sunflower, 10% palm and 10% corn (8S:1P:1C), 60% sunflower: 20% palm: 20% corn (6S:2P:2C), 40% sunflower, 30% palm and 30% corn (4S:3P:3C), 50% palm and 50% sunflower (5P:5S), 50% palm and 50% corn (5P:5C) and 50% sunflower and 50% corn (5S:5C) mixes were created by combining different feedstocks of waste frying oils as illustrates in Figure 2. These hybridization ratios were chosen to establish strict baseline parameters and systematically capture a comprehensive profile of saturated and unsaturated fatty acids. The 9:1 ratios evaluate the impact of introducing a minimal amount of a secondary component into a dominant feedstock matrix, while the binary 5:5 (50:50) hybrids assess the direct interactions between two oil types without ternary interference. Formulations with higher waste sunflower oil (S) fractions serve as the primary focus due to their promising baseline properties. Conversely, varying proportions of waste corn oil (C) and waste palm oil (P) were incorporated to isolate the specific influence of different unsaturated and saturated fatty acid concentrations. Ultimately, utilizing these specific binary and ternary mixtures allows for a rigorous, systematic comparison of how feedstock composition governs both biodiesel yield and its final physicochemical properties.

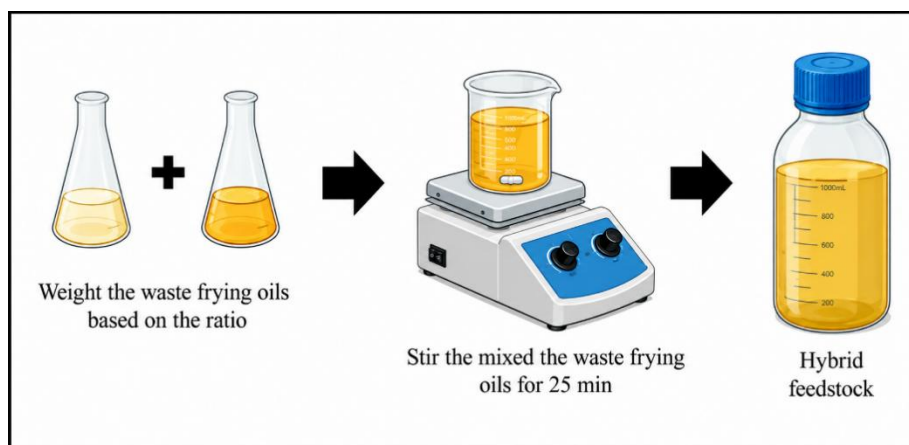


Figure 2. Preparation of hybrid waste frying oil feedstocks through feedstock hybridization at predetermined mixing ratios.

The production of fatty acid methyl ester (FAME) biodiesel involved the transesterification process of waste frying oil from palm, sunflower and corn. In this study, the molar ratio methanol to oil ratio used 6:1 ratio, using 1.0 wt.% of sodium hydroxide (NaOH) as the catalyst, reaction time 60 minutes and reaction temperature 65°C (Hsiao et al., 2022). The transesterification reaction was conducted at 65 °C because this temperature is close to the boiling point of methanol (64.7 °C), providing sufficient thermal energy to reduce oil viscosity, and improve mass transfer while minimising excessive methanol evaporation. Then, methanol and catalyst were added into conical flask. The process lasts for 15 min under stirring conditions using a magnetic stirrer on the hot plate. After sodium methoxide hybrid well, the waste frying oils sample was put into conical flask and stirred until 60 minutes as illustrated in Figure 3.

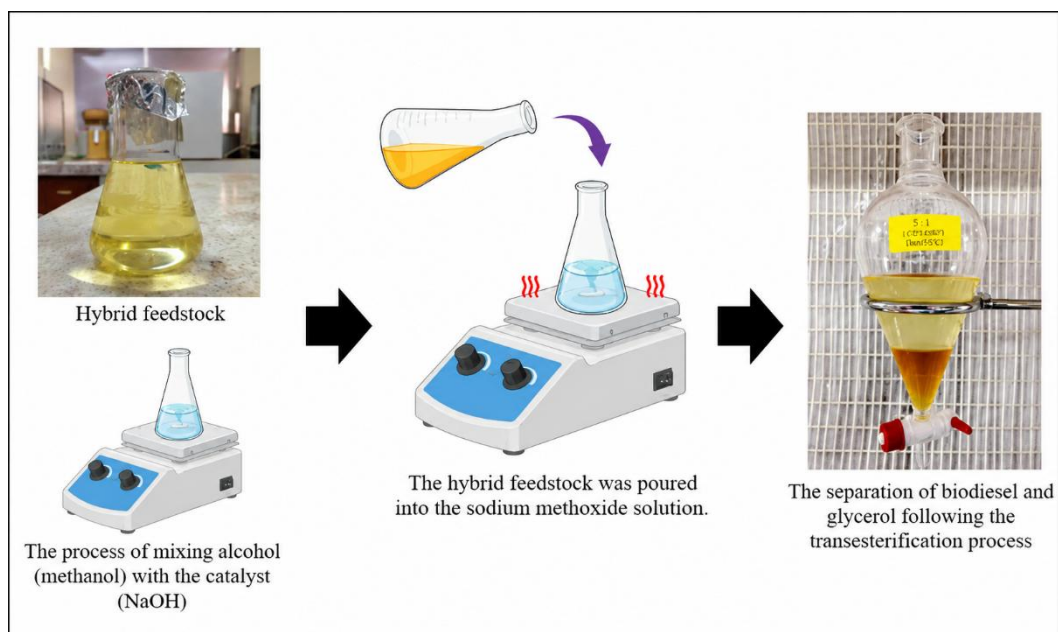


Figure 3. Transesterification process for biodiesel production from hybrid waste frying oil feedstocks.

The sample was placed into separating funnel overnight cooling in order to facilitate the vaporisation of the residual methanol and separated to remove the glycerol. The resulting biodiesel washed repeatedly with 50 mL portions of warm distilled water until the wash water became clear, indicating the removal of residual catalyst, glycerol, soap, and excess methanol (Bashir et al., 2018). The washed biodiesel was then dried in an oven at 110 °C for 40 min to remove residual moisture before further characterization. For each hybrid ratio and each individual WFO, the experiment was repeated three times using separate samples taken from the same prepared batch of WFO. All three experiments were carried out under the same conditions. Each experiment involved a fresh, independent preparation of the methanol, catalyst and hybrid oil matrix. The resulting biodiesel samples from these three independent chemical runs were subsequently characterized and all physicochemical properties were measured across these true chemical

replicates. The results are reported as the mean $\pm$ standard deviation ($n = 3$). The mass yield of biodiesel conversion was quantified to ascertain the percentage of biodiesel conversion according to Equation 1.

$$\text{Biodiesel yield (\%)} = \frac{W_b}{W_{WFO}} \times 100 \quad (1)$$

where W_b is mass of biodiesel (g), W_{WFO} is the mass of waste frying oil (g).

The parameters that were examined followed the biodiesel standard of ASTM 6751 and EN 14214 for density, kinematic viscosity, acid value, peroxide value, flash point and moisture content. The determination of the yield of methyl ester was conducted according to the ASTM 6751 and EN 14214 regulation procedure. After the yield were calculated, the biodiesel were storage in the glass bottle and placed in the refrigerator.

2.3. Characterization of Physicochemical Properties

To ensure scientific validity, all hybridization and transesterification reactions for the individual and hybrid biodiesels were executed in three completely independent experimental batches. All physicochemical characterizations were performed on these independent replicates, and the final results are reported as the mean $\pm$ standard deviation of these three distinct experiments.

The density of the samples was determined using the hydrometer method in accordance with ASTM D1298 (Standard Practice for Density, Relative Density (Specific Gravity), or API Gravity of Crude Petroleum and Liquid Petroleum Products by Hydrometer Method, 2017) and previous studies (Aisien et al., 2023; Hoang, 2021). Prior to measurement, the thermostatic water bath was adjusted to the required test temperature and the sample was transferred into a clean hydrometer cylinder. The cylinder was placed vertically in the thermostatic bath until the sample temperature stabilized within ± 0.1 °C. An appropriate hydrometer was then carefully immersed into the sample and allowed to float freely until equilibrium was reached. Any air bubbles adhering to the hydrometer or liquid surface were removed before recording the density. The density value was read at the intersection of the liquid surface with the hydrometer scale, and measurements were obtained for each of the three independent experimental batches. The results are reported as the mean $\pm$ standard deviation. The kinematic viscosity of biodiesel samples from each independent batch were measured at 40 °C in accordance with ASTM D445 (Hoang, 2021). Measurements were performed using a top-loading balance (Mettler Toledo, USA; ± 0.01 g), a pycnometer (ISOLAB, Singapore), a falling ball viscometer (Haake, Germany), a water bath, and a stopwatch (± 0.001 s).

The cloud point (CP) of the sample from each independent experiment was measured using the test jar method in accordance with ASTM D2500 (Hameed et al., 2022). Prior to analysis, the samples were filtered to remove moisture and filled into the test jar to the specified level. A thermometer was inserted into the jar, and the temperature was gradually lowered. At every 2 °C decrease, the jar was briefly removed for inspection. The CP was recorded as the temperature at which the first sign of cloudiness appeared.

The pour point (PP) was determined using the test jar method in accordance with ASTM D97 (Hameed et al., 2022). The PP is defined as the lowest temperature at which the sample can still flow. Measurements were conducted by cooling the specimen in 3 °C intervals. At each interval, the jar was removed from the cooling jacket, wiped to eliminate condensation, and tilted to observe movement. The PP was recorded as the temperature at which no flow was observed. The acid value and free fatty acid (FFA) content of waste frying oils (WFO palm, sunflower, and corn) were determined using the titration method. For each measurement, 1 g of oil from a distinct experimental batch was dissolved in 10 mL of isopropanol and titrated with 0.1 M potassium hydroxide solution using phenolphthalein as the indicator. Analyses were performed across the three independent batches to establish statistical significance. Acid value and FFA percentage were calculated using Equations 2 and 3.

$$AV \text{ (mg KOH/g)} = \frac{(KOH_i - KOH_b) \times N \times MW}{\text{Sample weight (g)}} \quad (2)$$

where AV is acid value (mg KOH/g), where KOH_i is the titrant volume for the sample (ml), KOH_b is the blank titrant volume (ml), N is the normality of potassium hydroxide, and MW is the molecular weight of KOH.

$$FFA \text{ (\%)} = \frac{AV}{2} \quad (3)$$

where FFA is free fatty acid (%), AV is acid value (mg KOH/g).

Meanwhile, for the saponification value the materials used were included potassium hydroxide, ethanol, hydrochloric acid, toluene, phenolphthalein powder, conical flasks, pipettes and burettes. The procedure followed the AOAC 920.160 standard method (Al-limoun, 2020; AOAC, 2000). Testing was executed using samples from each of the three independent replicates. Firstly, the chemical preparation

of 4% ethanolic KOH, 0.5N hydrochloric acid, blank sample and phenolphthalein indicator were prepared. After that, 5g of WFOs was pour and mixed with 50 ml of 4% ethanolic KOH in the reflux condenser. The mixture and the blank sample were heated for 30 minutes (min) and the if the layer not appear, the saponification are completed. The sample and blank allowed to cool at room temperature. Few drops of phenolphthalein were pipetted into the sample and blank sample and were shake. The sample and blank sample were turning the colour to pink. The sample and blank sample were agitated when titrated with 0.5N HCl solution until the pink colour disappears. The reading of 0.5N HCl solution used in the burette during titration were taken and recorded. The saponification value was calculated based on the Equation 4.

$$\text{Saponification value (mg KOH g}^{-1}\text{)} = \frac{(V_{\text{Blank}} - V_{\text{Sample}}) \times N \times \text{MW}}{\text{Sample weight (g)}} \quad (4)$$

where the V_{Blank} (ml) is the volume of HCl solution consumed for the blank sample, V_{Sample} (ml) is the volume of HCl solution consumed for the sample, N is the normality of HCl and MW is the molecular weight of potassium hydroxide.

In the iodine value test, the degree of unsaturation was measured and expressed as the grams of iodine absorbed per 100 grams (g) of samples evaluated across the three separate batches. The procedure followed the AOAC 920.159 standard (AOAC, 2000). The materials used included starch soluble powder, sodium thiosulfate, carbon tetrachloride, Wij's solution and potassium iodide. A 1% starch solution, 0.1 N sodium thiosulfate solution and a blank sample were also prepared for the analysis. In this procedure, IV flasks were used to place the sample and the blank sample. The sample were weighted range in between 0.25-0.66 g. The sample was mixed with 25 ml of carbon tetrachloride, then the mixture mixed with 25 ml of Wij's solution and shake for proper mixing. Potassium iodide crystal was added and placed around the surface of the stopper area of IV flasks and placed in the dark for 30 min. The sample were taken out from the dark place and the potassium iodide were rinse with 100 ml distilled water then 1 ml of 1% of starch solution were pipetted into the mixture. The sample were shaken and the colour changed to black colour sample. After that, the sample and blank sample were titrated with 0.1N sodium thiosulphate in the burette until the sample turn into milky white colour. The reading of burette was taken and recorded. The procedure of titration then continued with the blank sample. The iodine value was calculated based on the Equation 5.

$$\text{Iodine value (gI}_2\text{100g}^{-1}\text{)} = \frac{(V_{\text{Blank}} - V_{\text{Sample}}) \times N \times 12.69}{\text{Sample weight (g)}} \quad (5)$$

where the V_{Blank} is the 0.1N sodium thiosulphate consumed for the blank, V_{Sample} is the 0.1N sodium thiosulphate consumed for the sample, N is the normality of the sodium thiosulphate solution and 12.69 is the conversion factor from meq sodium thiosulphate to gram iodine.

Peroxide value (PV) was determined according to AOAC method 965.33 (AOAC, 2000) for each independent batch. Reagents and materials included glacial acetic acid, chloroform, soluble starch powder (indicator), potassium iodide (saturated solution), sodium thiosulfate titrant, and sodium carbonate. Ten grams of oil were accurately weighed into a conical flask and mixed with acetic acid–chloroform (3:2, v/v). One milliliter of saturated KI solution was added and the mixture was shaken for 1 minute, after which 30 mL of distilled water was added and shaken again for 1 minute. Following phase equilibration, 0.5 mL of starch indicator was introduced; the solution developed a dark color. The sample was titrated with 0.01 N sodium thiosulfate while vigorously agitating until the dark color disappeared and the solution turned nearly colorless. Burette readings before and after titration were recorded to obtain the titrant volume. The peroxide value was calculated using Equation 6.

$$\text{Peroxide value (meq kg}^{-1}\text{)} = \frac{V \times N \times 1000}{\text{Sample weight (g)}} \quad (6)$$

where, V is the volume of sodium thiosulfate consumed, N is the normality of sodium thiosulfate.

The flash point test was performed on the samples using the Pensky-Martens apparatus in accordance with ASTM D93(D93 Standard Test Methods for Flash Point by Pensky-Martens Closed Cup Tester, 2016). This apparatus operates as an automated closed-cup system and is capable of measuring flash points within a temperature range of 60°C to 190°C. The flash point is defined as the lowest temperature at which the vapor above a liquid fuel ignites in the presence of an ignition source. It is inversely related to fuel volatility, where lower flash points indicate higher volatility. The flash point, by contrast is the minimum temperature at which the fuel is capable of sustaining combustion for at least five seconds. Both parameters are critical for evaluating the flammability and fire hazard potential of biodiesel fuels. It helps to determine the temperature at which the fuel begins to emit flammable vapors, which is essential for safe handling, storage and transportation. The measurements were performed in triplicate and the results are reported as the mean $\pm$ standard deviation (SD).

The moisture content of the waste frying oils (WFOs), hybrid WFOs and biodiesel samples was determined using an A&D MS-70 Moisture Analyzer (A&D Company Ltd., Tokyo, Japan) which operates based on the loss-on-drying (LOD) principle. Prior to analysis, the instrument was calibrated according to the manufacturer's instructions. Approximately 2–5 g of each well-mixed sample was accurately weighed onto a clean aluminum sample pan and uniformly distributed to ensure consistent heating. The sample was then heated using the instrument's halogen heating system until a constant mass was achieved. The moisture content was automatically determined from the percentage mass loss during the drying process. The moisture content was calculated according to Equation 7:

$$\text{Moisture content (\%)} = \frac{W_i - W_f}{W_i} \times 100 \quad (7)$$

where W_i is the initial mass of the sample (g), and W_f is the final mass of the sample (g).

The calorific value of the biodiesel samples was determined using an IKA C200 bomb calorimeter (IKA-Werke GmbH & Co. KG, Germany) in accordance with ASTM D240 (Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter). Approximately 1.0 g of each biodiesel sample was accurately weighed into the combustion crucible. The bomb was sealed and charged with pure oxygen according to the manufacturer operating procedure before ignition. The sample was combusted under a pressurised oxygen atmosphere and the heat released during combustion was measured by the calorimeter. The higher calorific value was automatically calculated by the instrument.

The cetane number (CN) of the biodiesel samples was determined using a GBR-3035 Automatic Cetane Number Tester in accordance with ASTM D613 and ASTM D6890. Prior to analysis, the instrument was calibrated according to the manufacturer's instructions. Biodiesel samples were introduced into the instrument, and the cetane number was automatically determined based on the ignition quality of the fuel. All measurements were performed in triplicate and the results are reported as the mean $\pm$ standard deviation (SD).

Determination of fatty acid composition was performed by gas chromatography with flame ionization detection (GC-FID) following the procedure of [Da Silva et al. \(2022\)](#). Prior to analysis, fatty acids were derivatized to their methyl esters (FAMES) to enable separation and quantification. Analyses were carried out on an Agilent GC 7890A equipped with a flame ionization detector and a split injection system. For sample preparation, 50 mg of waste frying oil (WFO) was mixed with 0.95 mL n-hexane and 0.05 mL sodium methoxide, shaken thoroughly, and allowed to stand to precipitate sodium glyceroxide. The clear supernatant containing the biodiesel (FAMES) was then collected for injection. Injection volume was 1 μ L with a 1:100 split ratio and helium as carrier gas at 1 mL $\cdot$ min⁻¹. Inlet and detector temperatures were set at 240°C and 250°C, respectively, while the oven was held at 250°C for 1 min. Separation was achieved on a (50%-cyanopropyl)-methylpolysiloxane capillary column (30 m $\times$ 0.25 mm i.d., 0.25 μ m film). FAMES were identified by matching retention times to a Supelco 37-Component FAME Mix (Sigma-Aldrich). Prior to sample analysis, the GC-FID system was calibrated using a Supelco 37 Component FAME Mix (Sigma-Aldrich) to verify retention times and detector response.

Quantification used an internal standard approach to obtain response factors (RFs) which tridecanoic acid (C13:0) was added as internal standard (1 mg per sample) prior to methylation ([Rodrigues et al., 2023](#)). Assuming RF = 1, concentrations of individual FAMES were calculated from peak area ratios relative to the internal standard. Fatty acid composition was reported as percent (%) by area of each FAME peak area expressed relative to the total identified peak area (total = 100%). All measurements were performed in triplicate and the results are reported as the mean $\pm$ standard deviation (SD).

3. Statistical Analysis

All experiments were conducted in triplicate and the results are expressed as the mean $\pm$ standard deviation (SD) of three independent experiments (n = 3). Statistical analysis was performed using the Data Analysis ToolPak in Microsoft Excel (Microsoft Corporation, USA). One-way analysis of variance (ANOVA) was used to evaluate the effect of different waste frying oil hybrid ratios on biodiesel yield and physicochemical properties.

4. Results and Discussion

4.1. Fatty Acid of Waste Frying Oils from Palm, Sunflower and Corn Feedstock

[Figure 4](#) illustrates the fatty acid composition of biodiesel produced from different waste frying oil feedstocks. Palm waste frying oil biodiesel exhibited the highest proportion of saturated fatty acids (45.5 $\pm$ 0.4%) and the lowest proportion of unsaturated fatty acids (54.5 $\pm$ 0.7%) among the three feedstocks. In contrast, sunflower biodiesel contained the highest unsaturated fatty acid content (91.2 $\pm$ 0.6%) with only

8.8 ± 1.1% saturated fatty acids, whereas corn biodiesel was similarly dominated by unsaturated fatty acids (81.2 ± 0.4%) with a lower saturated fatty acid fraction (15.5 ± 0.6%). These differences reflect the inherent lipid composition of the original feedstocks and are consistent with the known characteristics of palm oil, which is naturally rich in palmitic acid (C16:0), while sunflower and corn oils contain high proportions of oleic (C18:1) and linoleic (C18:2) acids. Consequently, the greater saturation of palm biodiesel can contribute to improved oxidative stability and cetane number but is associated with less favourable cold-flow properties, whereas the higher unsaturation of biodiesels enhances low-temperature fluidity and may increase susceptibility to oxidative degradation (Sia et al., 2020a).

The variation in fatty acid composition as shown in Figure 4 provides the fundamental basis for the differences observed in the physicochemical properties of the biodiesels discussed in the subsequent sections. Saturated fatty acid methyl esters generally possess higher melting points and greater oxidative stability, whereas unsaturated fatty acid methyl esters improve cold-flow behaviour because the presence of carbon-carbon double bonds disrupts molecular packing and delays crystallisation (Binhweel et al., 2026). It should be noted that the reported percentages of saturated and unsaturated fatty acids do not always total exactly 100%. This is primarily attributed to analytical uncertainty associated with GC-FID quantification, rounding of individual fatty acid percentages, and the presence of trace or unidentified fatty acid components that were not included in the grouped saturated and unsaturated fractions. Such small deviations are commonly reported in fatty acid analyses and do not affect the interpretation of the fatty acid distribution or its relationship with biodiesel properties.

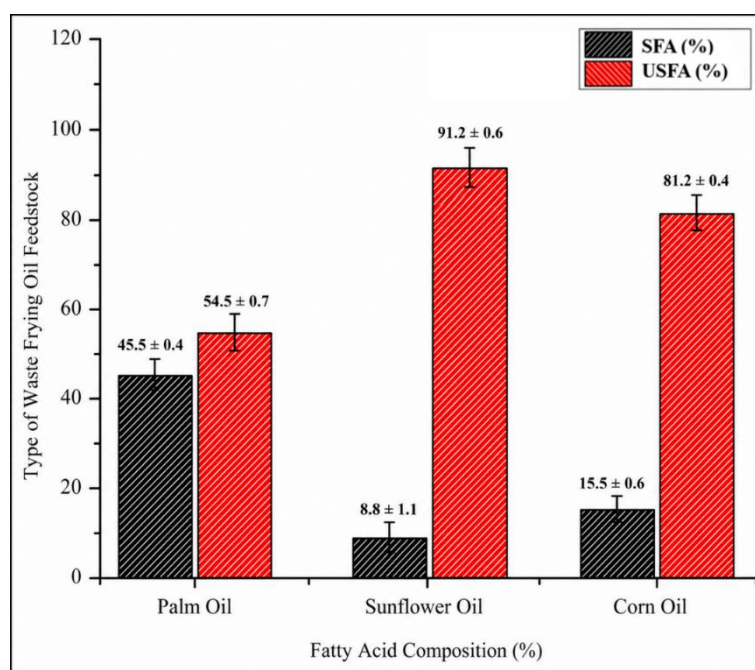


Figure 4. Percentage of fatty acids composition of saturated fatty acid (SFA) and unsaturated fatty acid (USFA) from different waste frying oils of palm, sunflower and corn.

The total composition of fatty acids in waste frying oil feedstocks is notably high, with levels exceeding 95%. This high percentage is essential for biodiesel production because the chemical structure of fatty acids directly affects the fuel quality and performance (Suzihaque et al., 2022). When the fatty acid content is at least 90%, it ensures that the feedstock has a substantial number of esters, which are the primary components of biodiesel. The total percentages of saturated and unsaturated fatty acids may not always sum to exactly 100% because the grouped values represent the major identified fatty acids detected by GC-FID. Minor fatty acids present at trace concentrations, together with analytical uncertainty arising from peak integration, detector response and rounding of individual fatty acid percentages, may account for the small differences from 100% (Cialìe Rosso et al., 2021).

High ester content is necessary for producing biodiesel that meets quality standards and exhibits desirable properties such as appropriate kinematic viscosity and flash point. Saturated fatty acids can contribute to fuel stability and energy content. While unsaturated fatty acids can improve cold flow properties and emissions (Deshmukh et al., 2019; Sia et al., 2020b). Therefore, assessing the fatty acid composition of waste frying oils is vital to achieving high-quality biodiesel that adheres to industry standards.

4.2. Characteristics of Waste Frying Oils

Table 1 presents the physicochemical properties of the waste frying oils (WFOs) derived from palm, sunflower, and corn feedstocks. The moisture content ranged from $2.60 \pm 0.71\%$ to $4.00 \pm 0.50\%$, with sunflower WFO exhibiting the highest moisture content, followed by corn ($3.17 \pm 0.30\%$) and palm ($2.60 \pm 0.71\%$) WFOs. In contrast, palm WFO recorded the highest acid value (1.13 ± 0.08 mg KOH/g) and free fatty acid (FFA) content ($0.57 \pm 0.20\%$), whereas sunflower WFO exhibited the lowest acid value (0.15 ± 0.06 mg KOH/g) and FFA content ($0.08 \pm 0.15\%$). Corn WFO showed intermediate values, with an acid value of 0.21 ± 0.07 mg KOH/g and an FFA content of $0.11 \pm 0.16\%$. These results indicate that the physicochemical characteristics of the WFOs varied according to the original feedstock despite being collected under similar frying conditions.

Table 1. Physicochemical properties of WFOs from palm, sunflower and corn.

Properties	WFO palm	WFO sunflower	WFO corn
Moisture content (%)	2.60 ± 0.71	4.00 ± 0.50	3.17 ± 0.30
Acid value (mg KOH/g)	1.13 ± 0.08	0.15 ± 0.06	0.21 ± 0.07
Free fatty acid (%)	0.57 ± 0.20	0.08 ± 0.15	0.11 ± 0.16

The higher acid value and FFA content observed in palm WFO can be attributed to the greater susceptibility of saturated triglycerides to hydrolytic degradation during repeated frying, resulting in the formation of free fatty acids through the cleavage of ester bonds (Abriana et al., 2019). In comparison, sunflower and corn WFOs exhibited considerably lower acid values, suggesting a lower degree of hydrolysis prior to transesterification. Although sunflower WFO contained the highest moisture content, its acid value remained comparatively low, indicating that moisture alone was not the dominant factor governing FFA formation. Instead, the combined effects of feedstock composition, thermal degradation during frying, and hydrolytic reactions influenced the physicochemical quality of the waste oils (Erickson et al., 2023). Since high FFA concentrations can promote soap formation during alkali-catalysed transesterification, the lower acid values observed for sunflower and corn WFOs indicate more favourable feedstock characteristics for biodiesel production under base-catalysed conditions.

The physicochemical characteristics shown in Table 1 are closely related to the fatty acid composition of the respective feedstocks, which subsequently governs the properties of the produced biodiesel. Palm WFO is characterised by a relatively higher proportion of saturated fatty acids, whereas sunflower and corn WFOs contain larger proportions of unsaturated fatty acids. These compositional differences influence not only the degradation behaviour of the oils during frying but also the resulting biodiesel properties including kinematic viscosity, cold-flow characteristics, iodine value and cetane number (Sidjabat, 2013). Therefore, understanding the initial physicochemical properties of the WFOs provides an important basis for interpreting the variations in biodiesel quality observed after transesterification and the rationale for employing feedstock hybridization to balance the advantages and limitations associated with individual waste frying oils.

4.3. Characteristics of Biodiesels

Table 2 presents the yield of biodiesel production from the hybrid feedstocks. The biodiesel yield ranged from $91.00 \pm 0.1\%$ to $98.54 \pm 1.1\%$, indicating that all feedstocks achieved relatively high conversion efficiencies. Among the individual feedstocks, sunflower waste frying oil produced the highest biodiesel yield ($98.54 \pm 1.1\%$), followed by corn ($92.48 \pm 2.1\%$) and palm ($91.04 \pm 2.3\%$) waste frying oils. The hybrid feedstocks also produced high biodiesel yields, ranging from $91.00 \pm 0.1\%$ to $96.12 \pm 1.2\%$. Among the hybrid feedstocks, the 9S:1C and 9S:1P feedstocks achieved the highest biodiesel yields of $96.12 \pm 1.2\%$ and $96.02 \pm 0.9\%$, respectively. In contrast, the 4S:3P:3C feedstock produced the lowest yield ($91.00 \pm 0.1\%$), followed closely by the 6S:2P:2C feedstock ($91.59 \pm 0.7\%$). In general, hybrids containing a greater proportion of sunflower waste frying oil tended to produce higher biodiesel yields than hybrids containing larger proportions of palm waste frying oil.

Table 2. Biodiesel yield (%) from different hybrid feedstocks.

Feedstock / Hybrid	Mass of biodiesel (g)	Yield (%)
Palm (P)	91.04 ± 2.30	91.04±2.3
Sunflower (S)	98.54 ± 1.10	98.54±1.1
Corn (C)	92.48 ± 2.10	92.48±2.1
90% Sunflower: 10% Palm (9S:1P)	96.02 ± 0.90	96.02±0.9
90% Sunflower: 10% Corn (9S:1C)	96.12 ± 1.20	96.12±1.2
80% Sunflower: 10% Palm:10% Corn (8S:1P:1C)	92.25 ± 1.30	92.25±1.3
60% Sunflower: 20% Palm:20% Corn (6S:2P:2C)	91.59 ± 0.70	91.59±0.7
40% Sunflower: 30% Palm:30% Corn (4S:3P:3C)	91.00 ± 0.10	91.00±0.1
50% Palm: 50% Corn (5P:5C)	95.90 ± 0.50	95.90±0.5
50% Palm :90% Sunflower (5P:5S)	92.00 ± 0.80	92.00±0.8
50% Sunflower: 50% Corn (5S:5C)	94.00 ± 1.10	94.00±1.1

Feedstocks rich in unsaturated fatty acids, which contain one or more double bonds in their carbon chains, tend to provide higher yields of biodiesel compared to feedstocks with a high proportion of saturated fatty acids (Jeon et al., 2019). The presence of double bonds in unsaturated fatty acids, such as oleic acid (mono-unsaturated) and linoleic acid (polyunsaturated), facilitates the transesterification reaction (Folayan et al., 2019a). This reaction involves the mixing of feedstock oils with an alcohol (methanol) and a catalyst (sodium hydroxide). The double bonds in unsaturated fatty acids make the carbon chains more reactive and amenable to conversion, resulting in higher rates of biodiesel yield (Biermann et al., 2021).

On the other hand, feedstocks that are predominantly composed of saturated fatty acids, such as palmitic and stearic acids, may pose challenges in the transesterification process due to their single-bonded carbon chains. These fatty acids are less reactive, leading to slower conversion rates and potentially lower yields of biodiesel (Borton et al., 2019). Furthermore, high levels of saturated fatty acids can increase the viscosity of the feedstock, affecting the overall process efficiency and the quality of the final biodiesel product (Mairizal et al., 2020). Feedstocks with a higher proportion of unsaturated fatty acids are generally preferred for biodiesel production due to their ability to achieve greater conversion rates and higher yields (Binhweel et al., 2025). This understanding helps guide the choice of feedstocks in order to maximize biodiesel output and efficiency.

As presented in Tables 4 and 5, the density of biodiesel varied according to the fatty acid composition of the waste frying oil feedstocks. Among the individual biodiesels, sunflower and corn biodiesels exhibited similar densities of 872.4 ± 2.0 and 872.2 ± 1.7 kg m⁻³, respectively, whereas palm biodiesel recorded a slightly lower density of 871.0 ± 1.5 kg m⁻³. Among the hybrid biodiesels, density values ranged from 871.7 ± 0.4 to 875.5 ± 0.7 kg m⁻³. The 5S:5C hybrid exhibited the highest density (875.5 ± 0.7 kg m⁻³), whereas the remaining hybrid biodiesels exhibited only slight variations, ranging from 871.7 ± 0.4 to 872.4 ± 0.4 kg m⁻³. Overall, all biodiesel samples satisfied the density requirement specified in EN 14214 (850–900 kg m⁻³), indicating that feedstock hybridization had only a minor influence on biodiesel density.

Table 3. Physicochemical properties of biodiesel measurement methods

Properties	ASTM D6751	EN14214	Method
Density (kg m ⁻³)	N/A	850-900	Hydrometer
Kinematic viscosity (mm ² s ⁻¹)	1.9 to 6.0	3.5 to 5.0	ASTM D445
Acid value (mg KOH/g)	0.5 max	0.5 max	Titration with KOH
Free fatty acid	N/A	N/A	Calculated from acid value
Cloud point (°C)	N/A	N/A	ASTM D2500
Pour point (°C)	N/A	N/A	ASTM D97
Iodine value (I ₂ /100g)	N/A	<120	Wij's solution
Peroxide value (meq/kg)	N/A	N/A	Titration
Flash point (°C)	>130	>101	ASTM D93
Saponification value (mg KOH/g)	N/A	N/A	AOAC 920.160
Cetane number	>47	>51	ASTM D613
Calorific value (MJ/kg)	-	-	ASTM D240

*N/A: Not applicable

Table 4. Physicochemical properties from individual biodiesels.

Properties	ASTM D6751	EN14214	Palm (P)	Sunflower (S)	Corn (C)
Density (kg m ⁻³)	N/A	850-900	871.0± 1.5	872.4 ± 2.0	872.2 ± 1.7
Kinematic viscosity (mm ² s ⁻¹)	1.9 to 6.0	3.5 to 5.0	3.52 ± 0.06	4.05 ± 0.19	4.01 ± 0.15
Acid value (mg KOH/g)	0.5 max	0.5 max	0.3±0.1	0.1±0.2	0.2±0.1
Free fatty acid	N/A	N/A	0.15±0.05	0.05±0.1	0.1±0.05
Cloud point (°C)	N/A	N/A	5.0 ± 0.2	-10.0 ± 0.3	-9.5 ± 0.4
Pour point (°C)	N/A	N/A	4.0 ± 0.2	-13.0 ± 0.1	-12.0 ± 0.1
Iodine value (I ₂ /100g)	N/A	<120	60.9 ± 0.4	129.2 ± 0.5	122.1 ± 0.7
Peroxide value (meq/kg)	N/A	N/A	30.5±1.1	39.5±0.7	33.3±1.5
Flash point (°C)	>130	>101	152.6 ± 1.1	164.9 ± 0.3	165.2 ± 0.8
Saponification value (mg KOH/g)	N/A	N/A	207.1 ± 0.7	201.2 ± 1.5	201.5 ± 1.1
Cetane number	>47	>51	58.6 ± 0.4	44.5 ± 0.9	45.8 ± 0.5
Calorific value (MJ/kg)	-	-	42.2 ± 0.4	41.3 ± 0.4	41.4 ± 0.4
Moisture content (%)	<0.5%	<0.5%	0.05 ± 0.71	0.1 ± 0.50	0.08 ± 0.30

Table 5. Physicochemical properties from different ratio of hybridization biodiesels

Properties	ASTM D6751	EN14214	9S:1P	9S:1C	8S:1P:1C	6S:2P:2C	4S:3P:3C	5P:5C	5P:5S	5S:5C
Density (kg m ⁻³)	N/A	850-900	872.2±0.3	872.4±0.4	872.1±0.5	872.0±0.3	871.9±0.1	871.7±0.5	871.7±0.4	875.5±0.7
Kinematic viscosity (mm ² s ⁻¹)	1.9 to 6.0	3.5 to 5.0	4.00±0.2	4.05±0.3	4.01±0.2	3.94±0.3	3.89±0.1	3.78±0.8	3.78±0.3	4.05±0.5
Acid value (mg KOH/g)	0.5 max	0.5 max	0.2±0.4	0.3±0.1	0.2±0.3	0.3±0.4	0.3±0.6	0.4±0.1	0.3±0.2	0.3±0.1
Free fatty acid	N/A	N/A	0.10±0.2	0.15±0.1	0.10±0.05	0.15±0.2	0.15±0.3	0.20±0.01	0.15±0.1	0.15±0.03
Cloud point (°C)	N/A	N/A	0.1±1.2	-3.0±0.5	1.0±1.0	2.0±0.3	4.0±0.8	0±0.6	-2.0±1.3	-9.0±1.4
Pour point (°C)	N/A	N/A	-3.0±1.8	-6.0±1.4	0.1±0.2	-10.0±2.3	-3.0±1.5	-1.0±1.0	-3.0±1.0	-11.0±0.8
Iodine value (I ₂ /100g)	N/A	<120	122.4±0.7	128.5±0.2	121.7±1.4	114.1±1.8	106.6±2.1	103.2±1.9	102.6±1.2	131.6±1.0
Peroxide value (meq/kg)	N/A	N/A	38.6±1.1	38.9±0.6	37.9±1.3	36.5±1.4	34.9±1.5	32.5±1.6	35.1±1.8	38.8±2.1
Flash point (°C)	>130	>101	163.7±1.4	164.9±1.1	163.7±2.0	162.5±1.2	161.3±1.3	153.5±0.4	153.5±0.8	151.1±0.2
Saponification value (mg KOH/g)	N/A	N/A	201.7±1.3	201.2±1.0	201.8±1.5	202.4±1.8	203.1±1.3	203.7±1.3	201.7±1.7	200.8±1.2
Cetane number	>47	>51	45.6±0.5	44.6±0.8	46.0±0.8	47.5±0.3	49.1±0.9	49.9±0.5	50.2±0.2	43.8±0.4
Calorific value (MJ/kg)	-	-	41.4±0.2	41.3±1.1	41.4±0.3	41.4±0.2	41.6±0.6	41.2±0.2	41.9±1.3	41.2±1.0

Increasing the percentage of C18 fatty acids compared to C16 fatty acids can indeed increase the density of biodiesel. C18 fatty acids of oleic acid (C18:1) and linoleic acid (C18:2) in the waste frying oil of sunflower and corn contribute more to the overall density of biodiesel because they have longer carbon chains compared to C16 fatty acids (palmitic acid). The longer carbon chains in C18 fatty acids result in larger and heavier molecules, which increase the density of biodiesel. Therefore, a higher percentage of C18 fatty acids compared to C16 fatty acids lead to higher density of biodiesel ([Srinivasan et al., 2020](#)). In general, a density closer to the middle of the standard range, around 850-900 kg m⁻³. Additionally, density influences in combustion process, affecting ignition timing, combustion duration and emission profiles. The performance of engine can be influenced by biodiesel density, as it ensures proper atomization during fuel injection, leading to efficient combustion and reduced emissions ([Hoang, 2021](#)),([Karpanai Selvan et al., 2022](#)). Deviations from the optimal density range can lead to engine knock, incomplete combustion, increased emissions and reduced engine efficiency.

4.4. Kinematic viscosity

The kinematic viscosity values of biodiesel produced from the individual and hybrid waste frying oil feedstocks are presented in [Tables 4 and 5](#). Among the individual biodiesels, sunflower and corn biodiesels exhibited the highest kinematic viscosity of 4.05 ± 0.19 mm² s⁻¹ and 4.01 ± 0.15 mm² s⁻¹, respectively, whereas palm biodiesel recorded the lowest value of 3.52 ± 0.06 mm² s⁻¹. Similarly, the 5S:5C hybrid biodiesel exhibited the highest kinematic viscosity (4.05 ± 0.50 mm² s⁻¹) among the hybrid, while the 5P:5C and 5P:5S biodiesels recorded the lowest values (3.78 ± 0.80 mm² s⁻¹ and 3.78 ± 0.30 mm² s⁻¹, respectively). The hybrid biodiesels exhibited only slight variation in viscosity, ranging from 3.78 to 4.05 mm² s⁻¹, indicating that feedstock hybridization had a relatively modest influence on this property.

Molecular structure of biodiesel derived from feedstocks with higher proportions of unsaturated fatty acids tends to have higher kinematic viscosity ([Kumbhar et al., 2022](#)). Unsaturated fatty acids, such as

oleic acid (C18:1) and linoleic acid (C18:2), contain one or more double bonds in their carbon chains, which can influence their physical properties, such as viscosity compared to saturated fatty acids like stearic acid (C18:0) that have no double bonds but the same number of carbon atoms. Additionally, the presence of double bonds in unsaturated fatty acids introduces kinks in the carbon chains, reducing the overall packing efficiency of the molecules (Mishra et al., 2021). This results in higher kinematic viscosity as the molecules are less able to flow past each other easily.

On another hand, the degree of unsaturation of biodiesel derived from feedstocks with higher levels of polyunsaturated fatty acids tends to have even higher kinematic viscosity compared to those with monounsaturated fatty acids (Adenuga et al., 2021). Density and viscosity are influenced by the overall fatty acid methyl ester composition, molecular weight, chain length and degree of unsaturation (Saeed et al., 2019). Feedstock hybridization modifies the balance of these molecular characteristics resulting in relatively small variations in density and viscosity among the biodiesel samples.

4.5. Acid Value and Free Fatty Acid

The acid value of biodiesel refers to the amount of free fatty acids present in the biodiesel. It is a critical parameter that indicates the level of acidity in the fuel. Based on Table 4, the acid value of waste frying oil from sunflower has the lowest value 0.1 mg KOH/g and hybrid biodiesel 5P:5C have the highest acid value (0.4 mg KOH/g). Acid value at Table 3 and 4 for all biodiesel meet the standard specification which below 0.5 mg KOH/g. This indicates that the measured physicochemical properties indicate that the produced biodiesel exhibits characteristics consistent with ASTM D6751 and EN 14214 requirements. The differences in acid values among the biodiesel samples can be attributed to variations in their fatty acid compositions. Biodiesel with higher proportions of unsaturated fatty acids tends to have lower acid values as unsaturated fatty acids are converted to esters during the transesterification process and reducing the concentration of free fatty acids (Folayan et al., 2019b),(Rasul et al., 2021).

A high acid value suggests a higher concentration of free fatty acids, which can lead to corrosion of engine components, formation of deposits and increased engine wear (OA et al., 2019). A low acid value is desirable as it indicates better fuel quality and increased engine durability. Acid value reflects the concentration of free fatty acids formed through hydrolytic and oxidative degradation of triglycerides during frying rather than the degree of fatty acid unsaturation alone (Venugopal & Dawn, 2026).

4.6. Cloud point

The cloud point (CP) represents the temperature at which the first wax crystals become visible during cooling and is an important indicator of the low-temperature behaviour of biodiesel. As shown in Tables 4 and 5, the cloud point varied considerably among the individual and hybrid biodiesels, reflecting differences in fatty acid composition while all samples were produced under identical transesterification conditions. Among the individual biodiesels, palm waste frying oil biodiesel exhibited the highest cloud point (5.0 ± 0.2 °C), whereas sunflower and corn biodiesels recorded substantially lower values of -10.0 ± 0.3 °C and -9.5 ± 0.4 °C, respectively. The relatively high cloud point of palm biodiesel is attributed to its higher proportion of saturated fatty acid methyl esters, particularly methyl palmitate (C16:0) and methyl stearate (C18:0), which readily crystallize upon cooling (Edith, 2012).

The hybrid biodiesels exhibited intermediate cloud points ranging from -9.0 ± 1.4 °C to 4.0 ± 0.8 °C, demonstrating that feedstock hybridization effectively modified the crystallization characteristics of the biodiesel. Hybrids containing higher proportions of palm waste frying oil, including 4S:3P:3C (4.0 ± 0.8 °C), 6S:2P:2C (2.0 ± 0.3 °C) and 8S:1P:1C (1.0 ± 1.0 °C), generally exhibited higher cloud points because the increased saturated fatty acid content promoted earlier wax crystal formation. (Liu & Tao, 2022). Conversely, hybrids containing larger proportions of sunflower and corn waste frying oils showed lower cloud points, indicating may improve resistance to crystallization at reduced temperatures. Among the hybrid biodiesels, the 5S:5C hybrid exhibited the lowest cloud point (-9.0 ± 1.4 °C), closely approaching the values obtained for the individual sunflower and corn biodiesels. Higher proportions of unsaturated fatty acid methyl esters, particularly linoleic (C18:2) and oleic (C18:1), reduce crystal packing because the double bonds introduce molecular kinks (Sendzikiene & Makareviciene, 2021). Consequently, crystallisation occurs at lower temperatures, resulting in lower cloud and pour points.

Increasing the palm waste frying oil fraction consistently increased the cloud point, whereas higher proportions of sunflower and corn waste frying oils reduced the temperature at which crystallization commenced. These observations demonstrate that feedstock hybridization provides an effective approach for modifying CP through adjustment of fatty acid composition while maintaining the overall physicochemical quality of the biodiesel.

4.7. Pour Point

As presented in [Tables 4](#) and [5](#), the pour point varied considerably among both the individual and hybrid biodiesels, reflecting differences in fatty acid composition while all samples were produced under identical transesterification conditions. Among the individual biodiesels, palm waste frying oil exhibited the highest pour point (4.0 ± 0.2 °C), whereas sunflower and corn biodiesels recorded substantially lower values of -13.0 ± 0.1 °C and -12.0 ± 0.1 °C, respectively. The relatively high pour point of palm biodiesel is attributed to its higher content of saturated fatty acid methyl esters, particularly methyl palmitate, which readily crystallize as temperature decreases. In contrast, the greater proportion of unsaturated fatty acid methyl esters in sunflower and corn biodiesels disrupts molecular packing through the presence of carbon-carbon double bonds, thereby delaying crystal formation and improving low-temperature fluidity ([Dwivedi & Sharma, 2013](#)).

The hybrid biodiesels exhibited intermediate pour points ranging from -11.0 ± 0.8 °C to 0.1 ± 0.2 °C, demonstrating that feedstock hybridization effectively modified the crystallization behaviour of the biodiesel. Hybrids containing higher proportions of palm waste frying oil, including 8S:1P:1C (0.1 ± 0.2 °C), 5P:5C (-1.0 ± 1.0 °C) and 5P:5S (-3.0 ± 1.0 °C), generally exhibited higher pour points because the increased saturated fatty acid content promoted crystal nucleation at relatively higher temperatures. Conversely, hybrids containing greater proportions of sunflower and corn waste frying oils showed improved cold-flow characteristics. The 5S:5C biodiesel exhibited the lowest pour point (-11.0 ± 0.8 °C), followed closely by 6S:2P:2C (-10.0 ± 2.3 °C), indicating that increasing the proportion of unsaturated feedstocks effectively reduced crystallization without completely eliminating the influence of saturated components ([Yaşar, 2020](#)). These observations demonstrate that relatively small changes in feedstock composition can noticeably influence the low-temperature behaviour of biodiesel.

Increasing the proportion of palm waste frying oil consistently increased the pour point because of its greater saturated fatty acid content, whereas increasing the sunflower and corn fractions reduced the pour point by increasing the degree of unsaturation ([Lanjekar & Deshmukh, 2016](#)). However, a higher degree of unsaturation may also increase susceptibility to oxidative degradation, indicating that the selection of an appropriate hybrid ratio should consider both low-temperature properties and oxidation resistance. The selection of an appropriate hybridization ratio represents a practical strategy for producing biodiesel with more balanced physicochemical properties than those obtained from individual waste frying oil feedstocks.

4.8. Iodine Value

The iodine value (IV) is an important indicator of the degree of unsaturation of biodiesel and reflects the number of carbon-carbon double bonds present in the fatty acid methyl esters (FAMES). As shown in [Table 4](#), biodiesel derived from palm waste frying oil exhibited the lowest iodine value of 60.9 ± 0.4 g I₂/100 g, whereas sunflower and corn biodiesels recorded the higher values of 129.2 ± 0.5 g I₂/100 g and 122.1 ± 0.7 g I₂/100 g, respectively. The lower iodine value of palm biodiesel is attributed to its relatively high proportion of saturated fatty acids, particularly palmitic acid (C16:0), which contain no double bonds and therefore contribute minimally to iodine absorption. In contrast, sunflower and corn waste frying oils are rich in polyunsaturated fatty acids, particularly linoleic acid (C18:2), resulting in substantially greater degrees of unsaturation and consequently higher iodine values ([Romano et al., 2021](#)).

The hybrid biodiesel samples exhibited iodine values ranging from 102.6 ± 1.2 to 131.6 ± 1.0 g I₂/100 g, demonstrating that feedstock hybridization directly influenced the overall unsaturation of the resulting biodiesel ([Table 5](#)). Hybrids containing higher proportions of palm waste frying oil, such as 5P:5S (103.2 ± 1.9 g I₂/100 g) and 5P:5C (102.6 ± 1.2 g I₂/100 g), exhibited markedly lower iodine values because the saturated fatty acids from palm oil diluted the highly unsaturated fatty acids contributed by sunflower and corn oils. Conversely, hybrids dominated by sunflower and corn waste frying oils, including 9S:1C (128.5 ± 0.2 g I₂/100 g) and the 5S:5C hybrid (131.6 ± 1.0 g I₂/100 g), retained relatively high iodine values owing to the predominance of polyunsaturated fatty acid methyl esters. These findings demonstrate that the iodine value can be effectively tailored through feedstock hybridization by controlling the ratio of saturated to unsaturated fatty acids.

Higher iodine values generally indicate greater susceptibility to oxidative degradation because the carbon-carbon double bonds present in unsaturated fatty acids readily react with oxygen during storage, forming hydroperoxides and secondary oxidation products. Consequently, biodiesel with excessive iodine values may exhibit reduced storage stability, increased peroxide formation, and the potential generation of insoluble gums and polymeric compounds that adversely affect fuel quality and engine performance. In contrast, biodiesel with lower iodine values generally possesses improved oxidative stability but may exhibit poorer cold-flow properties due to the higher content of saturated fatty acid methyl esters.

According to EN 14214, the maximum allowable iodine value for biodiesel is 120 g I₂/100 g to ensure adequate oxidative stability during storage and utilization. Among the hybrid biodiesels, only 5P:5S, 5P:5C, 4S:3P:3C, and 6S:2P:2C satisfied the EN 14214 requirement, while 9S:1P, 9S:1C, 8S:1P:1C, and 5S:5C remained above the specified limit. Although the 5S:5C biodiesel exhibited excellent cold-flow characteristics due to its high unsaturation, its iodine value suggests that additional measures, such as antioxidant additives or mix with more saturated feedstocks, may be necessary to improve oxidative stability for long-term storage.

4.9. Peroxide Value

Peroxide value (PV) is an important indicator of the primary oxidation state of biodiesel and reflects the concentration of hydroperoxides formed during the initial stages of lipid oxidation. As presented in Table 4, peroxide values differed considerably among biodiesels produced from the three waste frying oil feedstocks. Biodiesel derived from palm waste frying oil exhibited the lowest peroxide value (30.5 ± 1.1 meq O₂/kg), followed by corn biodiesel (33.3 ± 1.5 meq O₂/kg), whereas sunflower biodiesel showed the highest peroxide value (39.5 ± 0.7 meq O₂/kg).

Palm waste frying oil contained the lowest iodine value (60.9 g I₂/100 g), reflecting its relatively high proportion of saturated fatty acids, particularly palmitic acid (C16:0). Consequently, fewer lipid hydroperoxides are formed during storage, resulting in a lower peroxide value. In contrast, sunflower biodiesel exhibited both the highest iodine value (129.2 g I₂/100 g) and the highest peroxide value, indicating that the abundance of polyunsaturated fatty acids, particularly linoleic acid (C18:2), substantially increased the susceptibility of the biodiesel to primary oxidation. Corn biodiesel showed intermediate behaviour because it contained lower levels of polyunsaturated fatty acids than sunflower biodiesel but higher levels of unsaturated fatty acids than palm biodiesel.

The influence of feedstock composition became more evident after hybridisation (Table 5). Hybrid biodiesels exhibited peroxide values ranging from 32.5 ± 1.6 to 38.9 ± 0.6 meq O₂/kg, indicating that the oxidation behaviour of biodiesel could be modified through hybrid feedstock. Hybrids containing higher proportions of palm waste frying oil, particularly 5P:5C (32.5 ± 1.6 meq O₂/kg) and 5P:5S (35.1 ± 1.8 meq O₂/kg), exhibited lower peroxide values than hybrids dominated by sunflower and corn oils. The incorporation of palm oil effectively reduced the proportion of polyunsaturated fatty acid methyl esters, thereby decreasing the number of oxidation-sensitive double bonds available for hydroperoxide formation. Conversely, hybrids containing larger proportions of sunflower and corn oils, including 9S:1C (38.9 ± 0.6 meq O₂/kg), 9S:1P (38.6 ± 1.1 meq O₂/kg) and 5S:5C (38.8 ± 2.1 meq O₂/kg), retained relatively high peroxide values because of their greater degree of unsaturation.

5S:5C biodiesel exhibited a slightly higher peroxide value than sunflower biodiesel despite containing two different feedstocks. This observation suggests that peroxide formation is influenced not only by fatty acid composition but also by the previous thermal history of the waste frying oils, the extent of oxidation before biodiesel production, residual natural antioxidants, trace metal contaminants, and processing conditions (Lopresto et al., 2024). Waste frying oils obtained from different sources may have experienced different frying temperatures and durations, resulting in different levels of pre-existing oxidation products before transesterification. Although polyunsaturated fatty acids improve cold-flow behaviour, they are more susceptible to oxidation because the double bonds provide reactive sites for oxygen attack, leading to peroxide formation (Ahadi et al., 2026). The present findings show that increasing the proportion of palm waste frying oil effectively reduced peroxide formation, whereas higher proportions of sunflower and corn waste frying oils increased oxidative susceptibility.

4.10. Saponification Value

The saponification value (SV) provides an indication of the average molecular weight of fatty acid methyl esters present in biodiesel, with higher values generally corresponding to shorter average fatty acid chain lengths. As presented in Table 4, palm biodiesel exhibited the highest saponification value (207.1 ± 0.7 mg KOH g⁻¹), whereas sunflower and corn biodiesels showed lower values of 201.2 ± 1.5 mg KOH g⁻¹ and 201.5 ± 1.1 mg KOH g⁻¹, respectively. The relatively higher SV of palm biodiesel is attributed to its greater proportion of medium- and long-chain saturated fatty acids, particularly palmitic acid (C16:0), which require a greater amount of potassium hydroxide for complete saponification. In contrast, sunflower and corn biodiesels contain higher proportions of unsaturated C18 fatty acids, resulting in slightly lower saponification values. Although the differences among the individual biodiesels were relatively small, they reflect the inherent differences in fatty acid composition of the original waste frying oils.

A similar trend was observed for the hybrid biodiesels (Table 5), where the saponification values ranged from 200.8 ± 1.2 to 203.7 ± 1.3 mg KOH g⁻¹. Hybrids containing larger proportions of palm waste

frying oil, particularly 5P:5S ($203.7 \pm 1.3 \text{ mg KOH g}^{-1}$) and 5P:5C ($203.1 \pm 1.3 \text{ mg KOH g}^{-1}$), exhibited relatively higher saponification values than hybrids dominated by sunflower and corn oils. Conversely, the 5S:5C biodiesel recorded the lowest saponification value ($200.8 \pm 1.2 \text{ mg KOH g}^{-1}$), reflecting the predominance of longer-chain unsaturated fatty acids contributed by sunflower and corn feedstocks. These results indicate that feedstock hybridization modified the average fatty acid composition of the biodiesel, with increasing palm oil content progressively increasing the saponification value. However, the relatively narrow range observed among the feedstocks suggests that hybridization altered the fatty acid profile without substantially changing the overall molecular characteristics of the resulting biodiesel.

Although neither ASTM D6751 nor EN 14214 specifies a limit for saponification value, this parameter remains useful for assessing variations in feedstock composition and confirming the consistency of biodiesel quality. The saponification values among the hybrid biodiesels indicates that transesterification produced biodiesel with relatively similar average fatty acid chain lengths despite variations in the feedstock hybridization ratio. Therefore, the variations in saponification value are more appropriately interpreted as reflecting differences in fatty acid composition rather than indicating major changes in biodiesel quality.

4.11. Cetane Number

The cetane number (CN) is an important indicator of the ignition quality of biodiesel and is primarily influenced by the molecular structure of the fatty acid methyl esters (FAMES). As shown in Table 4, biodiesel produced from palm waste frying oil exhibited the highest cetane number (58.6 ± 0.4), followed by corn (45.8 ± 0.5) and sunflower (44.5 ± 0.9) biodiesels. The higher cetane number of palm biodiesel can be attributed to its greater proportion of saturated fatty acid methyl esters, particularly methyl palmitate, which possess straight-chain structures with fewer double bonds and therefore exhibit higher ignition quality (Lin & Wu, 2022). In contrast, sunflower and corn biodiesels contain higher concentrations of unsaturated fatty acids, especially linoleic acid (C18:2), whose multiple double bonds reduce cetane number by decreasing molecular stability during the ignition process.

A similar relationship was observed for the hybrid biodiesels (Table 5), where cetane numbers ranged from 43.8 ± 0.4 to 50.2 ± 0.2 . Hybrids containing higher proportions of palm waste frying oil generally exhibited higher cetane numbers than hybrids dominated by sunflower and corn oils. For example, 5P:5S (50.2 ± 0.2) and 5P:5C (49.9 ± 0.5) recorded the highest cetane numbers among the hybrid biodiesels, whereas 5S:5C exhibited the lowest value (43.8 ± 0.4). The gradual increase in cetane number with increasing palm oil content reflects the contribution of saturated fatty acid methyl esters, which increase the overall saturation of the biodiesel. Conversely, hybrids containing larger proportions of sunflower and corn oils retained relatively lower cetane numbers because of their higher content of polyunsaturated fatty acid methyl esters. These findings demonstrate that feedstock hybridization effectively modified the ignition quality of biodiesel through changes in fatty acid composition.

Palm biodiesel satisfied both the ASTM D6751 and EN 14214 cetane number requirements, whereas sunflower and corn biodiesels did not reach the minimum specification. Among the hybrid biodiesels, only 4S:3P:3C, 5P:5C, and 5P:5S complied with the ASTM D6751 minimum requirement of 47. These results indicate that increasing the proportion of palm waste frying oil improved cetane number by increasing the saturated fatty acid content, although excessive incorporation of highly unsaturated sunflower and corn oils reduced compliance with the cetane specification (Balfas et al., 2024). Therefore, feedstock hybridization offers a practical approach to tailoring ignition quality through manipulation of fatty acid composition. However, the hybridization ratio should be carefully selected to achieve an appropriate balance between cetane number and other desirable physicochemical properties.

4.12. Calorific Value

The calorific value represents the amount of heat released during the complete combustion of biodiesel and is an important indicator of its energy content. As presented in Table 4, palm biodiesel exhibited the highest calorific value ($42.2 \pm 0.4 \text{ MJ kg}^{-1}$), whereas sunflower and corn biodiesels recorded slightly lower values of $41.3 \pm 0.4 \text{ MJ kg}^{-1}$ and $41.4 \pm 0.4 \text{ MJ kg}^{-1}$, respectively. The relatively higher calorific value of palm biodiesel is associated with its greater proportion of saturated fatty acid methyl esters, which contain a higher carbon-to-hydrogen ratio and fewer double bonds than unsaturated fatty acid methyl esters. In contrast, the higher unsaturation of sunflower and corn biodiesels slightly reduces the energy released during combustion because double bonds lower the overall energy density of the fuel. Nevertheless, the differences among the individual biodiesels were relatively small, indicating that the three waste frying oil feedstocks possessed comparable energy contents despite differences in fatty acid composition.

A similar trend was observed for the hybrid biodiesels (Table 5), where calorific values ranged from 41.2 ± 0.2 to 41.9 ± 1.3 MJ kg⁻¹. Hybrid of 5P:5S (41.9 ± 1.3 MJ kg⁻¹), exhibited marginally higher calorific values than hybrids dominated by sunflower and corn oils. Conversely, the 5P:5C and 5S:5C biodiesels recorded the lowest calorific values (41.2 MJ kg⁻¹). The overall variation among the hybrid biodiesels was less than 2%, indicating that feedstock hybridization had only a modest influence on the energy content of the resulting biodiesel.

Although neither ASTM D6751 nor EN 14214 specifies a minimum calorific value for biodiesel, this property remains useful for comparing the intrinsic energy content of different feedstocks. The relatively narrow range observed in the present study suggests that hybridization primarily modified other physicochemical properties, such as cold-flow characteristics and cetane number, while maintaining comparable heating values. Therefore, the observed differences in calorific value are more appropriately attributed to variations in fatty acid composition than to fundamental changes in fuel chemistry. These findings indicate that hybridization of waste frying oils can be used to tailor selected fuel quality parameters without substantially altering the overall energy content of the biodiesel.

4.13. Flash Point

The flash point is an important safety-related property that represents the lowest temperature at which biodiesel releases sufficient vapour to ignite under specified conditions. As shown in Table 4, biodiesel produced from the individual waste frying oils exhibited flash points ranging from 152.6 ± 1.1 to 165.2 ± 0.8 °C, with palm biodiesel recording the lowest value (152.6 ± 1.1 °C) and corn biodiesel the highest (165.2 ± 0.8 °C). Despite these differences, all individual biodiesels exceeded the minimum flash point requirements specified by ASTM D6751 (>130 °C) and EN 14214 (>101 °C), indicating satisfactory removal of residual methanol following transesterification. The slightly lower flash point of palm biodiesel may be associated with differences in fatty acid composition and the presence of relatively shorter-chain saturated fatty acid methyl esters, whereas the higher flash points of sunflower and corn biodiesels may reflect the predominance of longer-chain unsaturated methyl esters and the low concentration of volatile components remaining after purification.

A comparable trend was observed for the hybrid biodiesels (Table 5), where flash points varied between 151.1 ± 0.2 and 164.9 ± 1.1 °C. Hybrid with higher proportions of sunflower and corn waste frying oils, such as 9S:1C (164.9 ± 1.1 °C) and 9S:1P (163.7 ± 1.4 °C), exhibited relatively higher flash points than hybrids containing larger proportions of palm waste frying oil. In contrast, the 5S:5C biodiesel recorded the lowest flash point (151.1 ± 0.2 °C), although it remained well above the minimum specification. Overall, the variation among the hybrid biodiesels was relatively small, suggesting that feedstock hybridization had only a limited influence on the volatility characteristics of the biodiesel. The consistently high flash points observed for all biodiesel further indicate that the washing and drying procedures effectively removed residual alcohol from the final products.

Although flash point is not directly governed by fatty acid composition alone, it is influenced by the combined effects of fatty acid molecular structure, residual methanol content, and the efficiency of post-reaction purification. Residual methanol is widely recognised as the primary factor responsible for lowering the flash point of biodiesel because of its high volatility. Since all biodiesel samples in the present study exhibited flash points substantially above the ASTM D6751 and EN 14214 limits, it can be inferred that the purification process was effective in minimizing volatile contaminants. Therefore, the relatively small differences observed among the individual and hybrid biodiesels are more likely attributable to minor variations in feedstock composition in biodiesel properties. These findings indicate that feedstock hybridization did not adversely affect the safety-related handling characteristics of the biodiesel and that all biodiesels-maintained flash points consistent with internationally accepted biodiesel specifications.

4.14. Fatty Acid of Biodiesel

Based on the comparative evaluation, the 5S:5C blend exhibited the most favourable cold-flow characteristics among the investigated hybrid biodiesel samples. Therefore, this hybrid was selected for further fatty acid composition analysis and compared with biodiesel derived from the individual palm, sunflower and corn waste frying oils. Figure 5 and Table 6 show the fatty acid composition of biodiesels. The fatty acid profiles of all biodiesels were predominantly unsaturated. The hybrid 5S:5C biodiesel exhibited the high unsaturated fatty acid content with $89.7 \pm 0.22\%$.

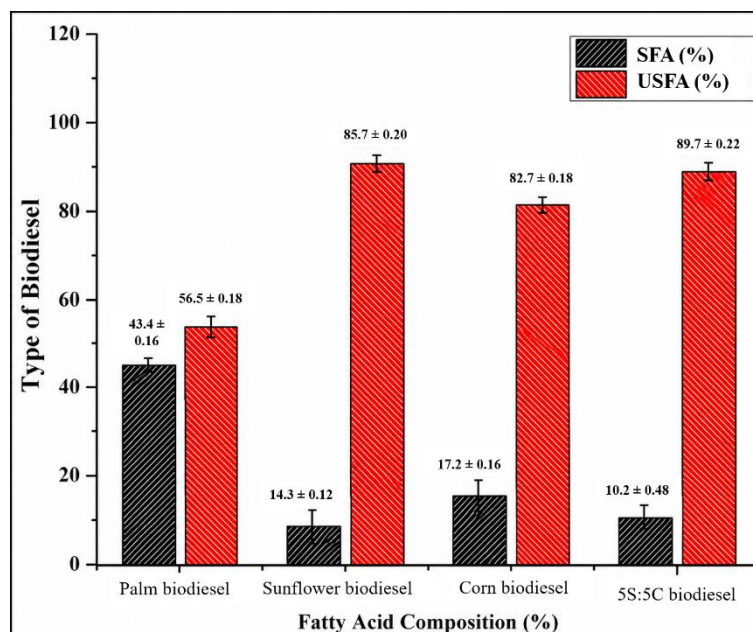


Figure 5. Fatty acid composition of biodiesels from different type of waste frying oils and hybrid.

Table 6. Fatty acid composition of biodiesel produced from palm, sunflower, corn and 5S:5C hybrid waste frying oil feedstocks.

Fatty acids	C:DB	Biodiesel			
		Palm (%)	Sunflower (%)	Corn (%)	5S:5C (%)
Lauric	C 12:0	0.30 ± 0.05	-	-	0.1±0.30
Myristic	C14:0	1.60 ± 0.03	-	-	0.1±0.12
Palmitic	C 16:0	40.10 ± 0.08	10.70 ± 0.08	13.60 ± 0.11	9.2±0.32
Stearic	C 18:0	1.40 ± 0.02	3.60 ± 0.04	3.60 ± 0.05	0.8±0.04
Oleic	C 18:1	45.40 ± 0.10	28.60 ± 0.06	30.30 ± 0.21	34.2±0.26
Linoleic	C 18:2	11.10 ± 0.08	57.10 ± 0.14	52.40 ± 0.16	55.2±1.50
Linolenic	C 18:3	-	-	-	0.3±0.03
ΣSFA		43.40 ± 0.16	14.30 ± 0.12	17.20 ± 0.16	10.2±0.48
ΣUSFA		56.5 ± 0.18	85.7± 0.20	82.7 ± 0.18	89.7±0.22

The prevalence of unsaturated fatty acids in biodiesels and 5S:5C biodiesel has implications to the properties. Unsaturated fatty acids such as linoleic acid and oleic acid are essential components that contribute to several desirable characteristics of biodiesel. Unsaturated fatty acid plays a crucial role in enhancing biodiesel performance by contributing to lower cold flow temperatures (Deshmukh et al., 2019). Lower cold flow temperatures ensure better fuel flow even at low temperatures, while improved density values and higher cetane numbers lead to better engine combustion efficiency and reduced emissions (Bari et al., 2020).

In contrast, biodiesel derived from palm oil, with its higher proportion of saturated fatty acids, may exhibit less favourable fuel properties. Saturated fatty acids tend to have higher melting points, which can lead to poor cold flow properties (Hazrat et al., 2020). The density of biodiesel is influenced by the overall fatty acid composition including carbon chain length and degree of unsaturation. Biodiesels containing higher proportions of unsaturated fatty acid methyl esters may exhibit slightly higher densities than those rich in saturated fatty acids (Jafarihaghighi et al., 2020). Therefore, understanding the relationship between fatty acid composition and biodiesel properties such as density, kinematic viscosity, acid value, cloud point and pour point is crucial for ensuring good quality of biodiesel.

5. Statistical Analysis of Physicochemical Properties

The evaluation of biodiesel fuel density using a one-way analysis of variance (ANOVA) demonstrated a highly significant difference across the various individual and hybridized formulations ($F(10, 22) = 4.02$, $p = 0.0031$), proving that shifting feedstock ratios directly alters the physical mass of the fuel. A post-hoc Tukey HSD test revealed that this variance is primarily driven by the 5S:5C (50% sunflower: 50% corn) binary hybrid, which experienced a non-linear density spike to $875.5 \pm 0.7 \text{ kg m}^{-3}$. This

elevation created statistically significant differences when compared to the lower-density baselines of pure palm $871.0 \pm 1.5 \text{ kg m}^{-3}$ and balanced multi-feedstock hybrids like 5P:5S, $871.7 \pm 0.4 \text{ kg m}^{-3}$. This unique behavior suggests that equal-part mix of sunflower and corn oils triggers a molecular compaction or synergistic packing of fatty acid methyl esters that increases volumetric mass. Conversely, no significant differences were observed among the remaining ternary and high-sunflower hybrids such as 9S:1P and 8S:1P:1C indicating that utilizing a dominant feedstock base successfully suppresses raw variance to maintain a highly stable density plateau between 871.7 and 872.4 kg m^{-3} . Crucially, while these structural variations are statistically distinct, the absolute physical difference across all groups remains under 0.5%, meaning every single hybrid complies perfectly with the EN14214 standard limits of 850-900 kg m^{-3} . The one-way analysis of variance (ANOVA) conducted on the kinematic viscosity data reveals no statistically significant difference across the pure and hybridized biodiesel groups ($F(10, 22) = 0.69$, $p = 0.7245$), demonstrating that altering the feedstock ratios does not cause drastic, unpredictable shifts in fluid flow resistance. Although palm oil biodiesel displays the lowest fluid resistance ($3.52 \pm 0.06 \text{ mm}^2 \text{ s}^{-1}$) due to its shorter or more saturated fatty acid configuration, and the 5S:5C, 9S:1C, and pure Sunflower fuels lie at the higher end ($4.05 \text{ mm}^2 \text{ s}^{-1}$), these absolute variations are statistically minor and swamped by internal sample variances particularly in the 5P:5C ($\pm 0.8 \text{ mm}^2 \text{ s}^{-1}$). This statistical uniformity is highly favorable from a fuel engineering perspective because every single formulation lies comfortably within both the liberal ASTM D6751 bounds (1.9 to $6.0 \text{ mm}^2 \text{ s}^{-1}$) and the stricter international EN14214 standards (3.5 to $5.0 \text{ mm}^2 \text{ s}^{-1}$).

Statistical evaluation of the cold-flow parameters yielded highly significant differences for both cloud point ($F(10, 22) = 123.38$, $p < 0.001$) and pour point ($F(10, 22) = 65.92$, $p < 0.001$). Palm oil biodiesel exhibits exceptionally poor cold-flow properties, possessing the highest CP ($5.0 \pm 0.2^\circ\text{C}$) and PP ($4.0 \pm 0.2^\circ\text{C}$) due to its rich concentration of saturated fatty acids, which crystallize easily at room temperature. Conversely, sunflower and corn biodiesels, which are dominated by unsaturated chains, provide outstanding low-temperature resilience with cold flow points plunging below -9.5°C . Post-hoc pairwise comparisons reveal that the 9S:1P, 9S:1C, 8S:1P:1C, and 6S:2P:2C hybrids act as statistically significant transition zones. For instance, hybrid minor fractions of sunflower into a palm base effectively neutralizes early crystallization, establishing a controlled, operational CP plateau between 0.1°C and 4.0°C . Most notably, the binary 5S:5C demonstrates an extreme cold-resilient synergy, yielding a significantly depressed CP of $-9.0 \pm 1.4^\circ\text{C}$ and a PP of $-11.0 \pm 0.8^\circ\text{C}$. This unique behavior creates a distinct statistical pair against the high-palm formulas, proving that equal-part pooling of high-unsaturation oils inhibits macro-crystalline network growth, vastly extending the sub-zero utility of the hybrid fuel.

The acid value remains highly uniform and statistically non-significant across all samples ($F(10, 22) = 0.24$, $p = 0.9881$), with mean values hovering tightly between 0.1 and 0.4 mg KOH/g. This absolute stability guarantees that feedstock hybridization does not risk structural degradation or corrosive properties, keeping every group securely below the maximum thresholds dictated by ASTM D6751 and EN14214 ($\leq 0.5 \text{ mg KOH/g}$). In contrast, the saponification value varies significantly ($F(10, 22) = 5.30$, $p = 0.0005$). This variation is driven exclusively by pure Palm biodiesel, which exhibits a uniquely high ester-to-mass ratio ($207.1 \pm 0.7 \text{ mg KOH/g}$) owing to its shorter molecular-weight carbon backbones. Post-hoc analysis confirms that all remaining bi-hybrid and tri-hybrid formulations settle into a statistically identical cluster ranging from 200.8 to 203.7 mg KOH/g. This homogeneity implies that even moderate multi-feedstock mixing successfully buffers individual feedstock molecular weight anomalies, standardizing the average chain lengths of the fuel mixture.

The iodine value generated the most extreme variance of the study ($F(10, 22) = 783.25$, $p < 0.001$), functioning as a direct reflection of structural carbon double bonds. Pure Palm biodiesel represents a low-unsaturation outlier at a mere $60.9 \pm 0.4 \text{ g I}_2/100\text{g}$. On the opposite end, sunflower, corn and the 5S:5C exhibit high unsaturation profiles, peaking up to $131.6 \pm 1.0 \text{ g I}_2/100\text{g}$. Post-hoc groupings classify these high-unsaturation mixtures as highly distinct pairs that violate the strict European standard limit EN14214 ($< 120 \text{ g I}_2/100\text{g}$). Crucially, the ANOVA highlights the engineering necessity of multi-feedstock hybridization: by structurally engineering mid-ratio hybrid configurations specifically the 6S:2P:2C (114.1 ± 1.8) and 4S:3P:3C (106.6 ± 2.1) ratios the biodiesel total unsaturation is successfully diluted. These specific hybrid bands form safe, compliant statistical pairs that satisfy international fuel specifications while preserving the flow advantages of unsaturated oils.

The flash point is highly dependent on the mixture ratio ($F(10, 22) = 82.74$, $p < 0.001$). Palm exhibits a significantly lower safety profile at $152.6 \pm 1.1^\circ\text{C}$, but all hybrid formulations containing a high proportion of sunflower or Corn see their thermal ignition boundaries pushed to a highly stable, safer ceiling of 161.3°C to 164.9°C . This physical change directly corresponds with cetane number dynamics, which vary sharply across groups ($F(10, 22) = 143.10$, $p < 0.001$). Pure Palm achieves an exceptionally high cetane rating (58.6 ± 0.4) due to its highly linear, saturated hydrocarbon strings that ignite rapidly

under compression, satisfying both ASTM D6751 (>47) and EN14214 (>51). When hybridizing into high-sunflower structures, the cetane values drop significantly, hitting a floor of 43.8 ± 0.4 in the 5S:5C hybrid. However, intermediate tri-hybrid like 6S:2P:2C (47.5) and 5P:5S (50.2) establish optimized statistical pairs that effectively balance safety flash boundaries with acceptable ignition delays. Lastly, the total thermal energy remains statistically uniform, as the calorific value showed no significant differences across all groups ($F(10, 22) = 0.64$, $p = 0.7666$), remaining constant at a dense 41.2 to 42.2 MJ/kg.

6. Limitations and Future Scope

Although the present study shows the potential of hybrid waste frying oil feedstocks for biodiesel production. The waste frying oil samples were collected from a single geographical location and may not fully represent the compositional variability of waste oils generated from different regions or cooking practices. In addition, only selected feedstock hybridization ratios were investigated and other hybridization ratios may further optimize biodiesel yield and physicochemical properties. The study was conducted at the laboratory scale and focused primarily on biodiesel production and physicochemical characterization. Therefore, engine performance, combustion behaviour, exhaust emissions, storage stability and oxidation stability were not evaluated. Furthermore, although several key physicochemical properties were assessed, not all fuel quality parameters specified in ASTM D6751 and EN 14214 standards were investigated. Future studies should include a broader sampling strategy, a wider range of feedstock hybridization ratios, comprehensive fuel quality analyses, oxidation stability assessment, pilot- or industrial-scale production, and engine performance and emission evaluations to further validate the applicability of hybrid waste frying oil feedstocks as sustainable biodiesel feedstocks.

7. Conclusions

This study demonstrated the potential of waste frying oils as renewable feedstocks for biodiesel production and showed that feedstock hybridization influenced the physicochemical properties of the resulting biodiesel. Among the evaluated hybrid biodiesels, the 5S:5C (sunflower–corn) hybrid showed the lowest cloud point (-9.0 ± 1.4 °C) and pour point (-11.0 ± 0.8 °C), indicating improved cold-flow characteristics compared with the other hybrid ratios. The 5S:5C hybrid also exhibited a density of 875.5 ± 0.7 kg m⁻³, kinematic viscosity of 4.05 ± 0.5 mm² s⁻¹, acid value of 0.3 ± 0.1 mg KOH/g, free fatty acid content of $0.15 \pm 0.03\%$, peroxide value of 38.8 ± 2.1 meq/kg, flash point of 151.1 ± 0.2 °C, saponification value of 200.8 ± 1.2 mg KOH/g, and calorific value of 41.2 ± 1.0 MJ/kg. Its fatty acid composition consisted of $10.2 \pm 0.48\%$ saturated fatty acids (SFA) and $89.7 \pm 0.22\%$ unsaturated fatty acids (USFA). However, the iodine value of 131.6 ± 1.0 I₂/100 g and cetane number of 43.8 ± 0.4 did not meet the corresponding limits specified in EN 14214 and ASTM D6751. These results demonstrate that hybridization can be used to modify selected biodiesel properties, particularly cold-flow characteristics, but the hybridization ratio must be carefully selected to balance different fuel-quality parameters. The findings provide experimental evidence on the influence of waste frying oil hybridization on biodiesel properties and support the valorization of waste frying oils as potential biodiesel feedstocks. Future studies should focus on oxidation stability, engine and emission performance and evaluation of additional fuel-quality parameters using different hybridization ratios.

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Author contributions

Wardah Senusi and Mardiana Idayu Ahmad: Conceptualization. Mohammad Aliff Shakir and Mardiana Idayu Ahmad: Methodology and Validation. Wardah Senusi: Writing—original draft preparation. Mardiana Idayu Ahmad and Mohammad Aliff Shakir: Writing—review and editing. Mardiana Idayu Ahmad: Supervision. Mardiana Idayu Ahmad: Project Administration. Mardiana Idayu Ahmad: Funding Acquisition. All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest Statements

The authors declare no conflict of interest.

Data availability statement

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Code availability

Not applicable.

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