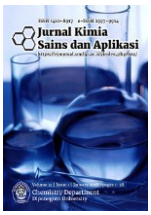
ISSN: 1410-8917
Jurnal Kimia Sains & Aplikasi
e-ISSN: 2597-9914

Jurnal Kimia Sains dan Aplikasi 29 (6) (2026): 379-387

Jurnal Kimia Sains dan Aplikasi
Journal of Scientific and Applied Chemistry

Journal homepage: http://ejournal.undip.ac.id/index.php/ksa



Quality Assessment of High-FAME Biosolar Fuels (B40–B60) Based on Indonesian Fuel Standards

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https://doi.org/10.14710/jksa.29.6.379-387

Article Info

Article history:

Received: 11th March 2026
Revised: 30th May 2026
Accepted: 02nd June 2026
Online: 31st July 2026

Keywords:
biosolar blend; fatty acid methyl ester; fuel quality evaluation; moisture adsorption; activated zeolite; cetane number

Abstract

The increasing utilization of biosolar fuels with high FAME (Fatty Acid Methyl Ester) content requires systematic quality evaluation to ensure compliance with fuel quality standards. This study evaluated biosolar fuels with different FAME fractions (B0, B40, B50, B60, and B100), with B40–B60 representing the main blending range and B0 and B100 serving as reference fuels. Fuel quality was assessed based on color, density, flash point, cetane number, distillation characteristics, total acid number (TAN), sulfur content, and water content, with reference to the Indonesian B40 diesel fuel specification under the Cetane Number 48 (CN 48) category as stipulated in Kepdirjen No. 384.K/MG.06/DJM/2024. The results showed that increasing FAME concentration produced a lighter fuel color and increased density from 839.7 kg m^{-3} (B0) to 876.5 kg m^{-3} (B100). Flash point increased from 55.6°C (B0) to 80.0°C (B100), while cetane number increased from 47.1 (B0) to 54.9 (B60), indicating improved fuel safety and ignition quality. Distillation temperatures increased with increasing FAME fraction due to the lower volatility of biodiesel components. The Total Acid Number increased from 0.09252 to 0.27320 mg KOH g^{-1}, whereas sulfur content decreased from 0.06622 to 0.00492 % (m/m), reflecting the inherently low sulfur composition of biodiesel. Water content increased substantially from 153.664 mg kg^{-1} (B0) to 901.970 mg kg^{-1} (B100) due to the hygroscopic nature of FAME. Activated zeolite treatment, applied at a dosage of 6 g per 500 mL fuel based on preliminary laboratory practice and adsorption conditions applied during the experimental design, reduced water content by approximately 9–24%; however, several blends remained above the allowable limit of 380 mg kg^{-1}. The relatively low flash point observed for B100 may indicate the presence of residual light components originating from production or handling processes and should therefore be interpreted as a limitation of the tested sample rather than a general biodiesel characteristic. These findings indicate that while biodiesel blending improves several fuel properties, effective moisture control remains essential for maintaining the quality and stability of high-FAME biosolar fuels.

1. Introduction

PT. Kilang Pertamina Internasional (KPI) Refinery Unit III Plaju is one of Indonesia's strategic refineries, playing a vital role in maintaining national energy security. Located in Palembang, South Sumatra, the refinery supplies fuel to the southern Sumatra region and contributes to national fuel distribution. Its operation is supported by a modern fuel quality control laboratory to ensure that all products comply with Indonesian National Standards (SNI), international testing standards such as ASTM, and technical specifications established by the Directorate General of Oil and Gas [1]. In addition to national regulations, conventional petroleum diesel quality is commonly benchmarked against ASTM D975

specifications, which define international performance and safety limits for commercial diesel fuels [2].

One of the main products under quality surveillance is biosolar, a blend of petroleum diesel with fatty acid methyl ester (FAME). In the blending classification system, B40 consists of 40% FAME and 60% petroleum diesel, while B30, B50, and B60 contain 30%, 50%, and 60% FAME, respectively. The implementation of biosolar is part of Indonesia's mandatory biodiesel program, aimed at reducing greenhouse gas emissions and supporting the national energy transition agenda [3].

The quality of biosolar is determined by critical parameters that directly influence storage safety, diesel engine performance, and regulatory compliance. These parameters include color, density, flash point, cetane number, distillation characteristics, total acid number (TAN), sulfur content, and water content [2, 4]. The acceptable limits for these properties are specified in the Decree of the Director General of Oil and Gas No. 384.K/MG.06/DJM/2024 concerning the quality specifications of B40 diesel fuel marketed domestically in Indonesia, which currently serves as the official national benchmark [1].

Increasing the FAME fraction in biosolar introduces new quality challenges. FAME is hygroscopic, more prone to oxidation, and may increase TAN, potentially leading to corrosion and accelerated fuel degradation [5]. At the same time, higher FAME content has been reported to improve cetane number and significantly reduce sulfur content, contributing to cleaner combustion characteristics [6]. Previous studies have also shown that biodiesel quality is strongly influenced by catalyst characteristics, feedstock composition, and processing conditions, thereby affecting fuel properties and product performance [7].

In addition to these physicochemical changes, higher biodiesel blending ratios may also introduce operational challenges in diesel engines. The hygroscopic nature of FAME facilitates water absorption during storage, which can accelerate corrosion of fuel system components and promote microbial growth in fuel tanks. Furthermore, the increased susceptibility of biodiesel-rich fuels to oxidation may lead to the formation of acidic compounds, gums, and deposits that can adversely affect fuel injectors, fuel filters, and combustion chamber cleanliness over prolonged operation. Previous studies have also reported that high-FAME blends may increase the risk of injector fouling, fuel filter plugging, and wear of metallic components due to the combined effects of moisture accumulation, oxidation products, and long-term fuel instability [5, 6].

Another important challenge associated with high-level biodiesel blends is their volatility behavior. Distillation characteristics and boiling-range distribution are recognized as key limiting properties for blends exceeding conventional biodiesel blending levels because they directly influence fuel evaporation, cold-start performance, ignition quality, catalyst light-off behavior, and the potential for fuel dilution in lubricating oil. As the FAME fraction increases, the higher boiling points and lower volatility of fatty acid methyl esters may alter fuel vaporization characteristics and consequently affect engine operation [8]. Therefore, understanding the distillation behavior of high-FAME biosolar fuels is essential for evaluating their technical feasibility and long-term operational performance.

However, most previous studies have focused on low to moderate blending levels, typically up to B30 (30% FAME, 70% diesel) or B40 (40% FAME, 60% diesel), leaving limited information regarding biosolar with higher FAME content [9]. This research gap becomes increasingly relevant as Indonesia's energy policy continues to promote higher biodiesel blending targets. Therefore, a comprehensive evaluation in accordance with official regulatory specifications is necessary to assess the technical readiness of higher FAME blends. Although ASTM D86 was originally developed and formally validated for petroleum fuels and relatively low biodiesel blending ratios, it remains the reference method specified in the current Indonesian B40 fuel standard for distillation control [1]. Consequently, in this study, ASTM D86 is employed as a comparative and regulatory evaluation tool to assess volatility trends in B40–B60 fuels, while acknowledging that results obtained for higher biodiesel fractions should be interpreted as indicative rather than strictly ASTM-validated performance data.

The transition toward higher biodiesel blending mandates presents both opportunities and technical challenges that must be systematically evaluated [8]. In this study, B40 is used as the regulatory benchmark in accordance with the current national specification under the CN 48 category [1], while B50 (50% FAME, 50% diesel) and B60 (60% FAME, 40% diesel) are evaluated to identify potential deviations from the established quality limits. This study aims to assess the physicochemical quality of high-FAME biosolar blends (B40–B60) in accordance with Indonesian fuel standards and to analyze their compliance and implications for future biodiesel blending policies.

2. Experimental

2.1. Equipment and Materials

This study used standard laboratory glassware, which was cleaned and oven-dried (Thermo Scientific™, USA) prior to use. Sample weighing was carried out using an analytical balance with a precision of ±0.0001 g. Fuel quality analyses were performed using a Petroleum Analyzer AF 650 for color determination, a density meter for density measurement, a Pensky–Martens Flash Point Tester (AM series) for flash point determination, a Cooperative Fuel Research engine (CFR F5, XCP) for cetane number analysis, an atmospheric distillation unit conforming to ASTM D86 for distillation characteristics, a Potentiometric Titrator AT-710 for total acid number determination, an X-ray Fluorescence Sulfur Analyzer (Epsilon 3X) for sulfur content analysis, and a Moisture Meter CA-31 for Karl Fischer water content determination.

The materials used in this study included automotive diesel fuel (B0) and FAME obtained from Refinery Unit III Plaju, PT. Pertamina (Persero). Natural zeolite in granular (spherical) form was used as the adsorbent material. Zeolite activation was performed using sulfuric acid solution (H_2SO_4, 0.5 M, Merck, ≥95%). Reagents for total acid number analysis were prepared in accordance with ASTM D664 and consisted of toluene (Merck, ≥99.5%), 2- propanol (Merck, ≥99.8%), potassium hydroxide (KOH, Merck, ≥85%), and distilled water. Deionized water was used throughout the experiments.

2.2. Sample Preparation

Biosolar blends were prepared by volumetric mixing of automotive diesel fuel (B0, 100% petroleum diesel) and fatty acid methyl ester (FAME, B100). The prepared compositions were B40, B50, and B60. In this study, B40, B50, and B60 contained 40%, 50%, and 60% (v/v) FAME blended with 60%, 50%, and 40% (v/v) diesel fuel, respectively. Prior to blending, diesel fuel and FAME were separately homogenized at room temperature. Blending was carried out in clean, dry glass containers by adding diesel fuel first, followed by the calculated volume of FAME to achieve the required composition. The mixtures were manually agitated for approximately 5–10 minutes to ensure uniformity.

After preparation, each blend was stored in airtight containers under typical laboratory conditions at approximately 22°C to minimize moisture absorption and contamination. Before analysis, samples were gently re-homogenized to maintain representative composition. Neat diesel (B0, 100% diesel) and pure biodiesel (B100, 100% FAME) were treated and stored under identical conditions for comparison. The diesel fuel (B0) and FAME (B100) samples used in this study were production samples obtained from PT. Kilang Pertamina Internasional Refinery Unit III Plaju. The samples were produced in May 2025 and retrieved from the refinery sample storage facility prior to analysis. Blending and fuel quality evaluations were subsequently conducted in July 2025. Therefore, the fuels investigated were materials stored for approximately 2 months before testing.

2.3. Color Analysis (ASTM D1500)

Fuel color was determined in accordance with ASTM D1500 [10] using a Petroleum Analyzer AF 650. Homogenized samples were placed in clean sample cells, and color values were measured according to the ASTM color scale. The reported values represent the average of duplicate measurements.

2.4. Density Measurement (ASTM D1298)

Density was measured according to ASTM D1298 [11] using a calibrated hydrometer. Homogenized fuel samples were transferred into a 100 mL graduated cylinder, and the hydrometer reading was taken at the stabilized meniscus level. The sample temperature was recorded, and density values were corrected to the reference temperature of 15°C using ASTM correction tables. Results were reported in kg/m^3.

2.5. Flash Point Determination (ASTM D93)

Flash point measurements were conducted using the Pensky–Martens closed cup method in accordance with ASTM D93 [12]. Samples were heated at a controlled rate while being continuously stirred. The flash point was defined as the lowest temperature at which a transient flame appeared on the vapor surface and was expressed in °C.

2.6. Cetane Number Determination (ASTM D613)

Cetane number was determined using a Cooperative Fuel Research (CFR F5) engine in accordance with ASTM D613 [13]. The engine was calibrated using primary reference fuels prior to testing. The cetane number was determined by comparing the combustion characteristics of the sample with those of standardized reference fuel blends under controlled operating conditions.

2.7. Distillation Characteristics (ASTM D86)

Distillation properties were evaluated following ASTM D86 [14] using an atmospheric distillation apparatus. A 100 mL sample was distilled under controlled heating conditions. The Initial Boiling Point (IBP), temperatures at 10, 50, and 90% volume recovery, and the Final Boiling Point (FBP) were recorded during the distillation process.

2.8. Total Acid Number (ASTM D664)

Total acid number (TAN) was determined using potentiometric titration in accordance with ASTM D664 [15]. Approximately 20 g of sample was dissolved in a mixed solvent consisting of toluene, 2-propanol, and deionized water, and the solution was titrated with a standardized KOH solution using a potentiometric titrator. TAN was calculated using Equation 1.

$$TAN = \frac{(V_s - V_b) \times N_{KOH} \times 56.1}{W} \quad (1)$$

Where, V_s is the volume of KOH solution used for the sample (mL), V_b is the volume of KOH solution used for the blank (mL), N_{KOH} is the normality of the KOH solution, 56.1 is the equivalent weight of KOH (mg/mmol), and W is the sample weight (g), and the results were expressed in mg KOH/g sample.

2.9. Sulfur Content Analysis (ASTM D4294)

Sulfur content was analyzed using X-ray fluorescence (XRF) spectroscopy in accordance with ASTM D4294 [16]. Fuel samples were placed into sample cups and analyzed using an XRF sulfur analyzer. Sulfur concentration was automatically calculated using the instrument calibration curve integrated into the analyzer software and reported as a percentage by mass (% m/m).

2.10. Water Content Analysis (ASTM D6304)

The water content of diesel fuel (B0), FAME (B100), and biodiesel blends (B40, B50, and B60) was determined using the Karl Fischer titration method in accordance with ASTM D6304 [17]. Approximately 1 mL of each homogenized sample was injected into the titration cell of a Moisture Meter CA-31. The water content was

automatically determined by the instrument and expressed in mg/kg.

2.11. Effect of Zeolite Treatment on Water Content

Natural zeolite was chemically activated by immersion in 0.5 M H_2SO_4 for 30 minutes, followed by washing with deionized water until the pH was neutral. Acid activation has been reported to modify the physicochemical properties of natural zeolite by increasing pore accessibility and altering surface characteristics, thereby enhancing its adsorption performance [18]. The adsorbent used in this study was molecular sieve zeolite 13X with a particle diameter range of 1.7–2.5 mm. Acid activation using 0.5 M H_2SO_4 was intended to remove mineral impurities and exchangeable cations from the zeolite surface, thereby increasing pore accessibility and the number of active adsorption sites. This treatment may also enhance the affinity of the zeolite toward water molecules and improve moisture adsorption performance in fuel matrices. The activated zeolite was dried at 100°C for 90 minutes and cooled to room temperature.

For adsorption treatment, 6 g of activated zeolite was added to 500 mL of each fuel sample, and the mixture was allowed to stand without agitation for 2 hours at room temperature (approximately 22°C). The adsorption performance was evaluated under static conditions to simulate practical storage treatment. The water adsorption capacity of the zeolite was not independently determined and is therefore considered a limitation of the present study. After treatment, the samples were filtered and reanalyzed for water content using ASTM D6304 [17] under identical analytical conditions.

3. Results and Discussion

The experimental results obtained in this study were evaluated based on the Indonesian diesel fuel quality specification issued by the Directorate General of Oil and Gas [1]. The measured properties of B0, B40, B50, and B60 were compared with the regulatory limits to assess their compliance with the CN 48 fuel specification.

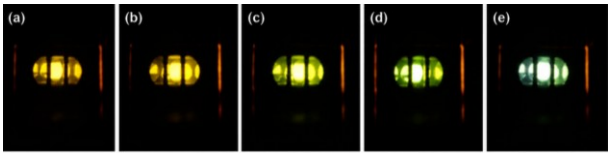

Figure 1. Visual appearance of biosolar fuels with different FAME contents showing ASTM D1500 color values: (a) B0 at 2.5, (b) B40 at 2.0, (c) B50 at 2.0, (d) B60 at 1.5, and (e) B100 at 0.5

Table 1. Density (ASTM D1298), flash point (ASTM D93), and cetane number (ASTM D613) of biosolar fuels

Fuel sample	Density at 15°C (kg/m³)	Flash point (°C)	Cetane number
B0	839.7	55.6	47.1
B40	854.9	65.5	51.4
B50	861.6	71.1	53.1
B60	862.6	75.6	54.9
B100	876.5	80	–

3.1. Fuel Color and Visual Stability

ASTM D1500 analysis showed a progressive decrease in color number with increasing FAME concentration. Diesel fuel (B0) exhibited the darkest appearance, while biodiesel (B100) showed the lightest color. Biosolar blends (B40–B60) displayed intermediate color intensities with a consistent lightening trend as the biodiesel fraction increased. The darker color of B0 is associated with its higher aromatic and heavy hydrocarbon content, whereas biodiesel consists primarily of fatty acid methyl esters with lower chromophoric compounds [19]. Although fuel color does not directly affect combustion performance, it can serve as an indicator of fuel oxidation, contamination, or degradation during storage. According to the Indonesian diesel fuel specification, the maximum allowable color value is 3.0 (ASTM D1500) [1]. The measured color values of all tested fuels remained below this limit, indicating that B0, B40, B50, and B60 comply with the regulatory requirement. The visual comparison of the tested fuels is presented in Figure 1.

3.2. Physicochemical Characteristics: Density, Flash Point, and Cetane Number

Density, flash point, and cetane number are critical parameters governing spray formation, ignition delay, combustion efficiency, and the operational safety of compression-ignition engines. The measured properties of B0, B40, B50, B60, and B100 are presented in Table 1.

3.2.1. Density and Fuel Injection Implications

As shown in Table 1, density increased progressively from 839.7 kg m^{-3} (B0) to 876.5 kg m^{-3} (B100), representing an overall increase of approximately 4.4%. The biosolar blends (B40–B60) exhibited a nearly linear increase in density with increasing FAME concentration, indicating uniform mixing and the absence of phase instability. Minor deviations from ideal linear blending behavior, particularly for B50, may be attributed to experimental measurement uncertainty and the inherent variability in density determination for blended fuel systems. Nevertheless, the observed values remain consistent with the overall trend of increasing density as FAME concentration increases. The higher density of biodiesel is due to the presence of long-chain fatty acid methyl esters, which contain polar ester functional groups and have a higher molecular mass than petroleum-derived hydrocarbons [3]. According to the Indonesian diesel fuel specification for CN 48 classification, the acceptable density range at 15°C is 815–880 kg m^{-3} [1]. The measured densities of B0 (839.7 kg m^{-3}), B40 (854.9 kg m^{-3}), B50 (861.6 kg m^{-3}), and B60 (862.6 kg m^{-3}) fall within this regulatory range, indicating compliance with the fuel specification.

In diesel engines using volumetric fuel injection systems, fuel density directly influences the injected fuel mass per cycle. Fuels with higher density deliver slightly greater fuel mass for the same injection volume, which may enrich the air–fuel mixture if the injection system is not recalibrated. Experimental studies have shown that fuel physical properties, particularly density and

viscosity, significantly affect the injection rate and mass flow characteristics in diesel injectors [20]. These properties also influence spray formation and atomization processes that govern fuel–air mixing and combustion efficiency in compression ignition engines [21]. Nevertheless, the moderate density increase observed in B40–B60 remains within the acceptable specification range, suggesting that these blends can be used in existing diesel injection systems without significant recalibration while maintaining stable spray formation and atomization.

3.2.2. Flash Point and Thermal Safety Characteristics

As shown in Table 1, the flash point increased substantially with biodiesel addition, rising from 55.6°C for B0 to 80°C for B100, corresponding to an increase of nearly 44%. This behavior reflects the inherently lower volatility and higher boiling range of fatty acid methyl esters compared to lighter petroleum-derived diesel hydrocarbons [22, 23]. The elevated flash point indicates reduced formation of flammable vapors at ambient conditions. According to the Indonesian diesel fuel specification, the minimum allowable flash point is 52°C [1]. The measured flash points of B0 (55.6°C), B40 (65.5°C), B50 (71.1°C), and B60 (75.6°C) all exceed this regulatory threshold, confirming compliance with the national fuel quality standard.

From a safety perspective, fuels with higher flash points exhibit lower vapor formation and improved resistance to accidental ignition during storage, handling, and transportation [24]. The progressive increase in flash point observed for B40–B60, therefore, indicates that biodiesel blending enhances thermal handling safety without compromising fuel stability. This characteristic is particularly advantageous in tropical regions, where elevated ambient temperatures can increase vapor generation and fire risk in low-flash-point fuels [25].

It should be noted that the measured flash point of the refinery-supplied B100 sample (80°C) was lower than the minimum values reported in commercial biodiesel specifications, such as ASTM D6751. This observation may indicate the presence of residual light components originating from production, storage, or handling processes. Therefore, the flash point reported in this study should be interpreted as a characteristic of the tested refinery sample rather than a representative value for specification-compliant biodiesel.

3.2.3. Cetane Number and Combustion Behavior

As presented in Table 1, a significant improvement in cetane number was observed with increasing FAME content, rising from 47.1 for B0 to 54.9 for B60. This corresponds to an enhancement of approximately 16.6% relative to conventional diesel fuel. The increase in cetane number is primarily attributed to the oxygenated molecular structure of fatty acid methyl esters, which promotes faster low-temperature oxidation reactions during the ignition stage and consequently shortens ignition delay time [6, 23]. Ignition delay plays a crucial role in determining combustion phasing, peak cylinder pressure, and pollutant formation in compression ignition engines. Fuels with higher cetane numbers generally exhibit smoother combustion behavior, reduced engine noise, and lower emissions of unburned hydrocarbons due to improved ignition quality [26].

According to the Indonesian diesel fuel specification issued by the Directorate General of Oil and Gas, the minimum cetane number required for CN 48 diesel fuel is 48 [1]. It should be emphasized that B0 was included in this study as a reference fuel to evaluate the influence of increasing FAME concentration on fuel properties. Therefore, compliance assessment with the B40 CN 48 specification was primarily intended for the biosolar blends (B40–B60), whereas B0 served as a baseline for comparative analysis rather than a regulatory compliance target.

As shown in Table 1, the measured cetane number of B0 (47.1) is slightly below this regulatory threshold, whereas the biosolar blends B40 (51.4), B50 (53.1), and B60 (54.9) all exceed the minimum requirement. These results indicate that the addition of biodiesel significantly enhances ignition quality and combustion stability in biosolar fuels. Nevertheless, higher cetane numbers improve ignition characteristics, but excessively high biodiesel fractions may affect other fuel properties, including cold-flow behavior and long-term oxidative stability. Previous studies have reported that biodiesel-rich fuels may exhibit higher cloud and pour points as well as increased susceptibility to oxidation during extended storage [4, 24]. Therefore, the selection of an appropriate biodiesel blending ratio should consider not only ignition performance but also fuel storage stability and operability under various climatic conditions.

3.3. Distillation Behavior and Volatility

The atmospheric distillation characteristics of B0, B40, B50, and B60 were determined using ASTM D86. The detailed distillation temperatures at different recovered volume fractions are presented in Table 2.

Table 2. Distillation characteristics of biosolar fuels determined using ASTM D86

Distillation point (°C)	B0	B40	B50	B60
IBP	153	165	170	198
10%	182	202	215	225
20%	200	228	249	270
30%	218	259	278	300
40%	232	284	299	310
50%	248	305	311	318
60%	270	309	319	323
70%	280	320	325	325
80%	309	325	328	330
90%	326	335	333	333
EP	330	356	342	353

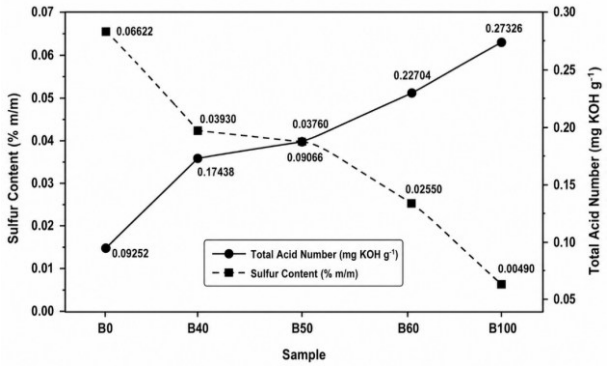

Figure 2. Sulfur content and TAN of B0, B40–B60, and B100. Both parameters are presented as line plots using dual vertical axes to facilitate comparison of their opposing trends with increasing FAME concentration

The distillation profiles exhibit a systematic shift toward higher boiling temperatures with increasing FAME content. The IBP increased from 153°C for B0 to 198°C for B60, while temperature differences in the mid-range fractions (T30–T60) reached approximately 60–70°C. This trend indicates a progressive reduction in fuel volatility as biodiesel concentration increases. The upward shift in boiling temperatures is attributed to the inherently higher boiling points and stronger intermolecular interactions of fatty acid methyl esters compared to petroleum hydrocarbons [27]. The longer carbon chains and polar ester functional groups of FAME require greater thermal energy for vaporization, resulting in heavier distillation fractions in B40–B60 blends.

Changes in volatility directly affect spray atomization, evaporation, and air–fuel mixing in compression ignition engines. The increase in early fraction temperatures (IBP–T20) suggests reduced light-end components, which may influence cold-start performance and ignition delay [28]. Conversely, higher boiling fractions can enhance thermal stability and reduce evaporative losses at elevated operating temperatures. Although ASTM D86 was originally developed for petroleum-based fuels and validated for relatively low biodiesel blends, deviations may occur at FAME concentrations above B30–B40 due to their distinct physicochemical properties [19]. Nevertheless, the method remains useful for comparative evaluation of volatility trends and for assessing compliance with the distillation parameter specified in the Indonesian B40 fuel standard. According to the Indonesian B40 CN 48 fuel specification, the maximum allowable temperature at 90% volume recovery (T90) is 370°C. As shown in Table 2, the measured T90 values of B0 (326°C), B40 (335°C), B50 (333°C), and B60 (333°C) all remained below this regulatory limit, indicating compliance with the distillation requirement. Overall, increasing FAME content reduces fuel volatility; however, the distillation characteristics of B40–B60 remain within acceptable operational limits.

The substantial increase in mid-range distillation temperatures (T30–T60) observed for B40–B60 indicates that a larger fraction of the fuel requires higher temperatures for vaporization. Under continuous engine operation, this behavior may reduce evaporation efficiency and delay fuel-air mixing in localized regions of the combustion chamber. Consequently, incomplete combustion may occur in some operating conditions, potentially increasing unburned hydrocarbon emissions and promoting the formation of carbonaceous deposits on injectors, piston crowns, and combustion chamber surfaces. These effects become increasingly important as the biodiesel fraction increases and fuel volatility decreases.

3.4. Chemical Quality Indicators: Sulfur Content and Total Acid Number

Chemical quality parameters provide important information regarding environmental impact, fuel stability, and long-term compatibility with engine components. Sulfur content and total acid number (TAN) are presented simultaneously in Figure 2 using dual vertical axes to compare their contrasting trends with increasing FAME concentration.

As shown in Figure 2 (left axis), sulfur content decreased progressively with increasing biodiesel fraction. Conventional diesel (B0) exhibited the highest sulfur concentration, whereas biodiesel (B100) contained only trace amounts. This reduction is attributed to the composition of biodiesel, which consists primarily of fatty acid methyl esters derived from vegetable oils or animal fats and contains negligible sulfur compared with petroleum-derived fuels [29, 30]. Consequently, blending biodiesel with petroleum diesel results in dilution, significantly reducing the overall sulfur concentration in biosolar fuels.

According to the Indonesian diesel fuel specification issued by the Directorate General of Oil and Gas, the maximum allowable sulfur content is 0.2 % (m/m) [1]. The sulfur levels measured in all tested fuels were below this regulatory threshold, indicating full compliance with national fuel quality standards. The reduction in sulfur concentration is environmentally beneficial because sulfur compounds in diesel fuel are oxidized during combustion to form sulfur oxides (SO_x), which contribute to air pollution, particulate emissions, and acid rain formation [6]. In addition, low-sulfur fuels improve the performance and durability of modern exhaust after-treatment technologies such as diesel oxidation catalysts (DOC) and diesel particulate filters (DPF) [31].

In contrast, the TAN increased with increasing biodiesel concentration, as illustrated in Figure 2 (right axis). The B0 sample exhibited the lowest acidity, while B100 showed the highest TAN value. This behavior reflects the chemical characteristics of fatty acid methyl esters, which are more susceptible to oxidative degradation during storage, forming free fatty acids and other acidic oxidation products [29, 32]. Based on the Indonesian diesel fuel specification, the maximum allowable TAN is 0.6 mg KOH g^{-1} [1]. Although all measured TAN values in this study remained well below the regulatory limit, the increasing acidity observed at higher biodiesel fractions suggests a potential limitation to long-term fuel stability. Elevated acidity may accelerate corrosion of metallic fuel system components, promote deposit formation, and negatively affect long-

term engine durability. Therefore, appropriate fuel storage management, including moisture control, limited oxygen exposure, and the application of antioxidant additives, is necessary to maintain the stability of biosolar fuels containing high biodiesel fractions.

3.5. Effect of FAME Concentration and Zeolite Treatment on Water Content

Water content plays a critical role in determining the storage stability, corrosion potential, and operational reliability of biosolar fuels. In this study, the water content of B0, B40, B50, B60, and B100 was determined using Karl Fischer titration in accordance with ASTM D6304. The measured values before and after zeolite treatment are presented in Figure 3. The diesel fuel (B0) and FAME (B100) samples used for blending were production samples obtained from PT. Kilang Pertamina Internasional Refinery Unit III Plaju. These samples were produced in May 2025 and analyzed in July 2025, representing an approximate storage period of two months prior to testing. This storage period reflects practical distribution and storage conditions that may occur before fuel utilization and is therefore relevant to evaluating moisture susceptibility, particularly in fuels with higher FAME fractions, which are known to exhibit hygroscopic behavior.

Before zeolite treatment, the water content increased substantially as FAME concentration increased. The measured values were 153.664 mg kg^{-1} for B0, 426.726 mg kg^{-1} for B40, 498.337 mg kg^{-1} for B50, 576.523 mg kg^{-1} for B60, and 901.970 mg kg^{-1} for B100. This trend confirms the hygroscopic nature of fatty acid methyl esters, whose polar ester functional groups facilitate hydrogen bonding with water molecules and enhance moisture absorption during storage [4, 29]. According to the Indonesian diesel fuel specification issued by the Directorate General of Oil and Gas, the maximum allowable water content is 380 mg kg^{-1} [1]. Based on this limit, B40 already exceeded the regulatory threshold, while larger deviations were observed for B50 and B60, and the highest water content was detected in B100. Elevated water levels in diesel fuels may accelerate oxidative degradation, promote microbial growth, and increase the risk of corrosion in fuel storage tanks and injection system components [33].

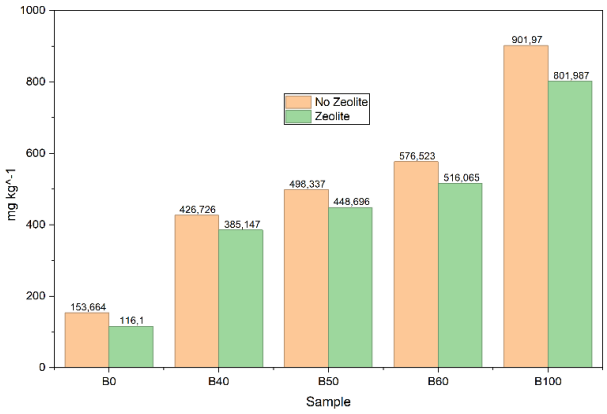

Figure 3. Water content of B0, B40–B60, and B100 before and after zeolite treatment was measured using ASTM D6304

After zeolite treatment, the water content decreased to 116.100 mg kg^{-1} (B0), 385.147 mg kg^{-1} (B40), 448.696 mg kg^{-1} (B50), 516.065 mg kg^{-1} (B60), and 801.987 mg kg^{-1} (B100). These results correspond to moisture reductions of 24.45%, 9.74%, 9.96%, 10.49%, and 11.09%, respectively. In this experiment, 6 g of zeolite was added to 500 mL of fuel, corresponding to a zeolite-to-fuel ratio of 12 g L^{-1}. Considering the density range of the tested fuels (839–876 kg m^{-3}, Table 1), the zeolite dosage corresponds approximately to 13.7–14.3 g of zeolite per kilogram of fuel. This ratio provides a useful reference for evaluating the effectiveness of moisture adsorption under the experimental conditions.

The higher reduction observed in B0 suggests more efficient moisture removal in non-polar hydrocarbon matrices. In contrast, blends containing FAME exhibited lower and relatively uniform reduction efficiencies (approximately 9–11%). This behavior may be attributed to competitive interactions between water molecules and the polar ester functional groups present in FAME. Water molecules can form hydrogen-bonding networks with ester oxygen atoms, thereby increasing their retention within the fuel matrix and reducing their accessibility to zeolite adsorption sites [34]. Furthermore, although molecular sieve 13X has pore dimensions sufficiently large for water adsorption, a portion of the water may remain associated with FAME via intermolecular interactions, thereby limiting overall adsorption efficiency. As a result, moisture removal becomes less effective as the FAME concentration increases. The adsorption performance of activated zeolite is known to depend on pore accessibility, surface activation, and the interactions between adsorbates and adsorption sites, which can significantly influence moisture removal efficiency [35].

4. Conclusion

This study evaluated the fuel quality of biosolar with different FAME fractions (B0, B40, B50, B60, and B100) based on the Indonesian B40 CN 48 fuel specification. Increasing the FAME concentration resulted in a lighter fuel color and a higher density. Flash point and cetane number also increased, indicating improved fuel safety and ignition quality. Distillation temperatures increased with increasing FAME content, reflecting the lower volatility of biodiesel components. The Total Acid Number (TAN) increased gradually, suggesting reduced oxidative stability at higher biodiesel fractions. Conversely, sulfur content decreased significantly with increasing FAME concentration, demonstrating the environmental advantage of biodiesel blending. Water content remained the main limiting parameter due to the hygroscopic nature of FAME. Although activated zeolite treatment reduced moisture levels, several blends still exceeded the maximum allowable limit of 380 mg kg^{-1} specified for B40 CN 48 fuel. These findings indicate that moisture management remains a critical challenge for the implementation of high-FAME biosolar fuels. For industrial applications, additional dehydration strategies such as multi-stage adsorption systems, optimized molecular sieve treatment, vacuum dehydration, or fuel drying prior to storage may be considered to further

reduce water content and improve long-term fuel stability. Overall, the results demonstrate that most physicochemical and combustion-related properties of B40–B60 blends remain favorable and comply with the evaluated fuel quality requirements. However, effective moisture control is essential to ensure regulatory compliance and operational reliability. Since B50 and B60 represent biodiesel blending levels beyond the current B40 mandate, the present findings provide useful preliminary information regarding the opportunities and technical challenges associated with future higher-FAME biodiesel implementation in Indonesia.

Acknowledgement

The authors would like to express their sincere gratitude to PT. Kilang Pertamina Internasional Refinery Unit III Plaju for providing the facilities and technical support that enabled this research to be conducted. The authors also gratefully acknowledge the guidance and cooperation of the Engineering & Development Manager and the laboratory team at Refinery Unit III Plaju, whose support significantly contributed to the completion of this study.

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